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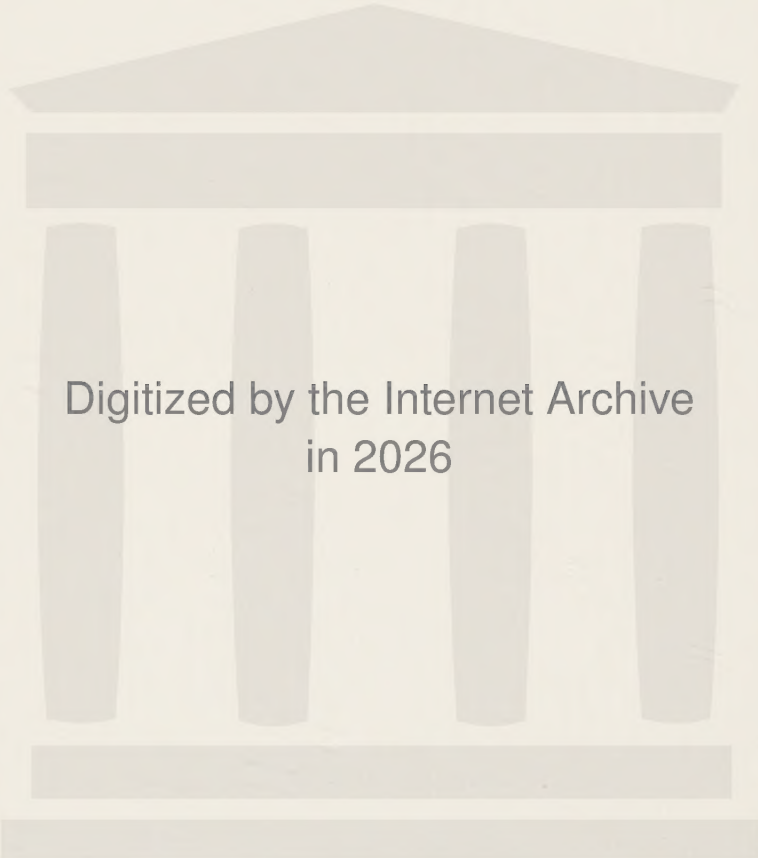
APPLICATION OF IMPULSE RADAR
TO CIVIL ENGINEERING

By

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Lund 1982.

Department of Engineering Geology
1982



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Department of Engineering Geology

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DOCTORAL T H E S I S

APPLICATION OF IMPULSE RADAR

TO CIVIL ENGINEERING

B y

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PREFACE

The present thesis deals with the application of Impulse Radar to Civil Engineering Problems. The radar, developed to be used for mapping subsurface structures, is applied to some novel situations .

The work was carried out at the Department of Engineering Geology, Lund University of Technology.

I am indebted to Leif Bjelm for changing the direction of the peat project, so that I could finance the radar system, and for constant support for my ideas.

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Lund, November 1st 1982

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1 THEORETICAL FOUNDATIONS AND ELECTRICAL PROPERTIES

This will be a display of the mathematics that is used in connection with impulse radar measurements. It has two main sources: electromagnetic wave theory and geometrical optics. The latter area is applicable whenever the wavelength is considerably shorter than the objects that the wave interferes with and when the material can be considered an isolator. There will be no derivations of the statements since most of them are of ordinary textbook content. The purpose is to display the parameters that govern the success of impulse radar use and give an idea of what is possible and what is not.

An impulse radar is a wide-band radar i.e. it transmits energy over a frequency band in contrast to pulse radars operating at one single frequency which is turned on and off. Since many of the involved phenomena are frequency dependant complex numbers are used. For rapid calculations an estimate can be obtained by using the center frequency of the transmitting antenna.

The Fast Fourier Transform FFT is a convenient way to move from time domain, i.e. the actual impulse to the frequency domain, i.e. the frequency spectrum of the impulse.

Electromagnetic Wave Propagation

The wave equation, EDMINSTER, J., A. 1975

$$\gamma^2 = j\omega\mu (\sigma + j\omega\epsilon) \quad (1.1)$$

where

$\gamma = \alpha + j\beta$ the wave number	$\mu_r = 1$ relative susceptibility
$\omega = 2\pi f$ (rad/s)	$\epsilon_0 = 10^{-9}/36\pi$ (F/m) permittivity
$\mu = \mu_0\mu_r$ (H/m)	$\epsilon_r =$ relative permittivity
$\epsilon = \epsilon_0\epsilon_r$ (F/m)	1-81 for the geologic materials
$\sigma =$ electric conductivity	
$\mu_0 = 4\pi \cdot 10^{-7}$ (H/m)	$j = \sqrt{-1}$
susceptibility	

has the solution

$$\alpha = \omega \sqrt{\frac{\mu \epsilon}{2} \left(\sqrt{1 + \left(\frac{\sigma}{\omega \epsilon}\right)^2} - 1 \right)} \quad (1.2)$$

$$\beta = \omega \sqrt{\frac{\mu \epsilon}{2} \left(\sqrt{1 + \left(\frac{\sigma}{\omega \epsilon}\right)^2} + 1 \right)} \quad (1.3)$$

$$\lambda = \frac{2\pi}{\beta} \quad (1.4)$$

$$c = \frac{\omega}{\beta} \quad (1.5)$$

$$c = \lambda \cdot f \quad (1.6)$$

where

λ = the wave length

c = phase velocity

f = the frequency

α = attenuation factor

β = phase shift constant

The electromagnetic field E_0 originating at $z = 0$, $t = 0$ will be described by $E(z, t)$ at a distance z and time t .

$$E(z, t) = E_0 \cdot e^{-\alpha \cdot z} \cdot e^{j(\omega t - \beta z)} \quad (1.7)$$

The first exponential function is the attenuation term and the second the propagation term. From the first e f it is seen that the attenuation is $1/e$ at a distance $z = 1/\alpha$ which is also called the skin depth δ .

$$\delta = \frac{1}{\alpha} \quad (1.8)$$

The intrinsic impedance Z is the relation between the electric field $\vec{E}$ and the magnetic field $\vec{H}$.

$$Z = \frac{\vec{E}}{\vec{H}} \quad (1.9)$$

Z is a complex quantity that is calculated according to

$$Z = \sqrt{\frac{j\omega\mu}{\sigma + j\omega\epsilon}} \quad (1.10)$$

the magnitude $|Z|$ and phase shift θ are calculated from

$$|Z| = \left(\sqrt{\frac{\mu}{\epsilon}} \right) / \left(4 \sqrt{1 + \left(\frac{\sigma}{\omega \epsilon} \right)^2} \right) \quad (1.11)$$

$$\theta = \frac{1}{2} \tan^{-1} \left(\frac{\sigma}{\omega \epsilon} \right) \quad (1.12)$$

Optics

As previously mentioned there are two criterions that must be valid to permit the use of optics theory when dealing with impulse radar. The wave length must be short in relation to the illuminated objects and the media must be almost an isolator. The fundamental difference between an impulse and a continuous wave-field must also be considered when applicable.

For horisontal polarization and incidence angle ϕ from nadir we obtain HECHT 1975

$$r_h = \frac{\sqrt{\epsilon_1} \cos \phi - \sqrt{\epsilon_2 (1 - (\epsilon_1/\epsilon_2) \sin^2 \phi)}}{\sqrt{\epsilon_1} \cos \phi + \sqrt{\epsilon_2 (1 - (\epsilon_1/\epsilon_2) \sin^2 \phi)}} \quad (1.13)$$

For vertical polarization we obtain

$$r_v = \frac{\sqrt{\frac{1}{\epsilon_1}} \cos \phi - \sqrt{\frac{1}{\epsilon_2} (1 - \epsilon_1/\epsilon_2) \sin^2 \phi}}{\sqrt{\frac{1}{\epsilon_1}} \cos \phi - \sqrt{\frac{1}{\epsilon_2} (1 - \epsilon_1/\epsilon_2) \sin^2 \phi}} \quad (1.14)$$

For monochromatic waves r_v can be zero while r_h can never be zero. Corresponding incidence angle ϕ_B is known as Brewster's angle

$$\sin \phi_B = \sqrt{\frac{\epsilon_2}{\epsilon_1 + \epsilon_2}} \quad (1.15)$$

Total reflection occurs when

$$\frac{\epsilon_1}{\epsilon_2} \cdot \sin^2 \phi > 1 \quad (1.16)$$

since $\sin^2 \phi$ is always ≤ 1 it is a prerequisite that $\epsilon_1 > \epsilon_2$.

Refraction occurs when a ray passes an interface between two media with different dielectric constants. If ϕ_1 is the angle of incidence relative to the normal and ϕ_2 is the angle of refraction relative to the normal Snell's law takes the form

$$\epsilon_1 \sin^2 \phi_1 = \epsilon_2 \sin^2 \phi_2 \quad (1.17)$$

In a layered media a ray will take a route which corresponds to the shortest optical path length OPL. This is known as Fermat's principle

$$\text{OPL} = \min \left[\frac{1}{c} \sum \sqrt{\epsilon_i} \cdot s_i \right] \quad (1.18)$$

Assume an impulse incident at an angle ϕ_i and refracted at an angle ϕ_r according to Snell's law. The relative permittivity of the first medium is ϵ_1 and that of the reflector is ϵ_2 . Fermat's equations states that

$$r_{\text{hor}}^{\text{pol.}} = \frac{\sqrt{\epsilon_1} \cos \phi_i - \sqrt{\epsilon_2} \cos \phi_r}{\sqrt{\epsilon_1} \cos \phi_i + \sqrt{\epsilon_2} \cos \phi_r} \quad (1.19)$$

$$r_{\text{vert}}^{\text{pol.}} = \frac{\sqrt{\epsilon_2} \cos \phi_i - \sqrt{\epsilon_1} \cos \phi_r}{\sqrt{\epsilon_1} \cos \phi_r + \sqrt{\epsilon_2} \cos \phi_i} \quad (1.20)$$

$$R_{\text{hor}}^{\text{pol.}} = \frac{\sin^2 (\phi_i - \phi_r)}{\sin^2 (\phi_i + \phi_r)} \quad (1.21)$$

$$R_{\text{vert}}^{\text{pol.}} = \frac{\tan^2 (\phi_i - \phi_r)}{\tan^2 (\phi_i + \phi_r)} \quad (1.22)$$

If a monochromatic wave falls on a rough plane interface then the majority of the reflected energy comes from the first Fresnel zone. The i :th Fresnel zone has a radius R_{Fi}

$$R_{Fi} = \left(\lambda r_0 + \frac{2i-1}{4} \lambda^2 \right)^{\frac{1}{2}} \quad (1.23)$$

where r_0 is the distance from the source to the reflector. The number of activated zones depends on the pulse length.

Interference occurs when two waves mix. If they are in phase constructive interference occurs and if they are out of phase we obtain destructive interference. Let E_{01} and E_{02} be two sources of electromagnetic energy. At time t and distance r

$$E_{01}(r,t) = E_{01} \cos (k_1 \cdot r - \omega t + \phi_1) \quad (1.24)$$

$$E_{02}(r,t) = E_{02} \cos (k_2 \cdot r - \omega t + \phi_2) \quad (1.25)$$

where

k = propagation number $k = \frac{\omega}{v}$

ϕ = originating phase

When the waves mix they are added and the energy is obtained by squaring the sum.

$$E^2 = (E_1 + E_2)(E_1 + E_2) = E_1^2 + E_2^2 + 2 E_1 E_2 \quad (1.26)$$

where the last term is the interference term. The phase difference δ is obtained from

$$\delta = (k_1 \cdot r) - (k_2 \cdot r) + \phi_1 - \phi_2 \quad (1.27)$$

Reflection of Electromagnetic Waves

If a planar wave-field falls into an infinite interface between two media 1 and 2 some energy will be reflected and the remainder transmitted. The reflected field strength is described by the reflection coefficient r

$$r = \frac{Z_2 - Z_1}{Z_2 + Z_1} \quad (1.28)$$

where Z is the impedance of the media.

The power reflection coefficient R is simply the square of the reflection coefficient $R = r^2$.

If the angle of incidence from the vertical is ϕ the formula presented by CIHLAR & ULABY 1974 can be used for horizontal polarization

$$R_{\text{hor}} = \frac{[(p - U)^2 + q^2]}{[(p + U)^2 + q^2]} \quad (1.29)$$

where

$$p = \frac{1}{\sqrt{2}} ((\alpha_1 + U^2 - 1)^2 + \beta_2^2)^{\frac{1}{2}} + (\alpha + U^2 - 1)^{\frac{1}{2}} \quad (1.30)$$

$$q = \frac{1}{\sqrt{2}} ((\alpha_1 + U^2 - 1)^2 + \beta_2^2)^{\frac{1}{2}} - (\alpha + U^2 - 1)^{\frac{1}{2}} \quad (1.31)$$

$$U = \cos \phi \quad (1.32)$$

Should the reflector be thin e.g. a thin ore-body the following expression may be used

$$R = \frac{((1 - z_1/z_2)(1 + z_2/z_3) + (1 + z_1/z_2)(1 - z_2/z_3)) e^{-2j\gamma_2 t}}{((1 + z_1/z_2)(1 + z_2/z_3) + (1 - z_1/z_2)(1 - z_2/z_3)) e^{-2j\gamma_2 t}} \quad (1.33)$$

where

t = thickness of the reflector

z = impedance of media 1, 2 and 3. 2 is the layer

$$\gamma_2 = \alpha_2 + j\beta_2$$

If the reflector is a stratified media, the following method presented by HEVENOR (-) can be applied. See also WAIT 1970. For horizontal polarization

$$R_{\text{hor}} = \frac{(\alpha_1 + j\beta_1) \cos \phi_1 - \sqrt{A(o)} \cdot (w + jv)}{(\alpha_1 + j\beta_1) \cos \phi_1 + \sqrt{A(o)} \cdot (w + jv)} \quad (1.34)$$

where

$$w = \frac{2 A^2(o) \sin \gamma(o) + A'(o)}{2 A^{3/2}(o)} \quad (1.35)$$

$$v = \frac{2 A^2(o) \cos \gamma(o) - A(o) \gamma'(o)}{2 A^{3/2}(o)} \quad (1.36)$$

where

$$A(z) = [(\omega^2 \mu_0 \epsilon(z) + L)^2 + (\omega \mu_0 \sigma(z) - M)^2]^{\frac{1}{4}} \quad (1.37)$$

$$\gamma(z) = \frac{1}{2} \cos^{-1} \left[\frac{\omega^2 \mu_0 \epsilon(z) + L}{A^2(z)} \right] \quad (1.38)$$

where

$$L = (\alpha_1^2 - \beta_1^2) \sin^2 \phi_i \quad (1.39)$$

$$M = 2 \alpha_1 \beta_1 \sin^2 \phi_i \quad (1.40)$$

α and β are given by 1.2 and 1.3.

In order to evaluate (1.34) the denominator is multiplied by the complex conjugate, as is done for Z in (1.10) and by using (1.35) to (1.40)

$$a = \alpha \cos \phi - \sqrt{A(o)} \cdot w \quad (1.41)$$

$$b = \beta \cos \phi - \sqrt{A(o)} \cdot v \quad (1.42)$$

$$c = \alpha \cos \phi + \sqrt{A(o)} \cdot w \quad (1.43)$$

$$d = \beta \cos \phi + \sqrt{A(o)} \cdot v \quad (1.44)$$

The magnitude $R(\omega)$ and phase $\theta(\omega)$ are calculated by

$$|R(\omega)| = \sqrt{\frac{(ca + bd)^2 + (cb - da)^2}{(c^2 + d^2)^2}} \quad (1.45)$$

$$|\theta(\omega)| = \tan^{-1} \left[\frac{cb - da}{ca + bd} \right] \quad (1.46)$$

Radar Range

The capacity of the radar to detect an echo of power P_r , if the transmitted power is P_t , is called the sensitivity S or performance figure of the radar set

$$S = \frac{P_t}{P_r} \quad (1.47)$$

It is usually given in dB

$$S = 10 \log \left(\frac{P_t}{P_r} \right) \quad (1.48)$$

In practice the limiting factor is the thermal noise in the receiver $P_r > P_{\text{noise}}$.

$$P_{\text{noise}} = 1.6 \cdot 10^{-20} \cdot \Delta f W \quad (1.49)$$

Δf = the receiver bandwidth

Part of the sensitivity lies in the antenna gain G_A .

$$G_A = \frac{4\pi a^2}{\lambda^2} \quad (1.50)$$

where

a = antenna aperture

This statement says that the gain of the antenna is proportional to the antenna size measured in wave lengths squared.

The total power loss TPL is spreading loss + absorption loss.

$$TPL = 10 \log_{10} \left[\frac{64\pi^3 z^4}{g\sigma G^2 \lambda^2} \right] + 2 \cdot z \cdot 10 \log_{10} (\alpha) \quad (1.51)$$

where

$g\sigma$ = target backscatter gain, cross section product

z = range

If $S > TPL$ there will be a registration of the reflection.

For a rough plane, specular reflector with power reflection coefficient R , the $g\sigma$ -product will be

$$g\sigma = \pi \left(\lambda z + \frac{\lambda^2}{4} \right) R \quad (1.52)$$

For a smooth plane specular reflector, we obtain for $g\sigma$

$$g\sigma = \pi \cdot z^2 \cdot R \quad (1.53)$$

For a point target, the Rayleigh law of scattering applies and

$$g\sigma = \frac{64\pi^5 a^6 f^4}{c^4} \quad (1.54)$$

where a is the radius of the scattering sphere.

A special form of gain is refractive gain G_R described by GUDMANDSEN 1972. If an antenna is elevated to such a height h that the ground is in the far field, there will be a gain due to refraction of the radiation when it is passing the air/ground interface, Figure 1.1. Consider a perfect reflector lying at depth z in the ground. Due to the refraction, the illuminated area will become smaller and the reflected energy density will become greater.

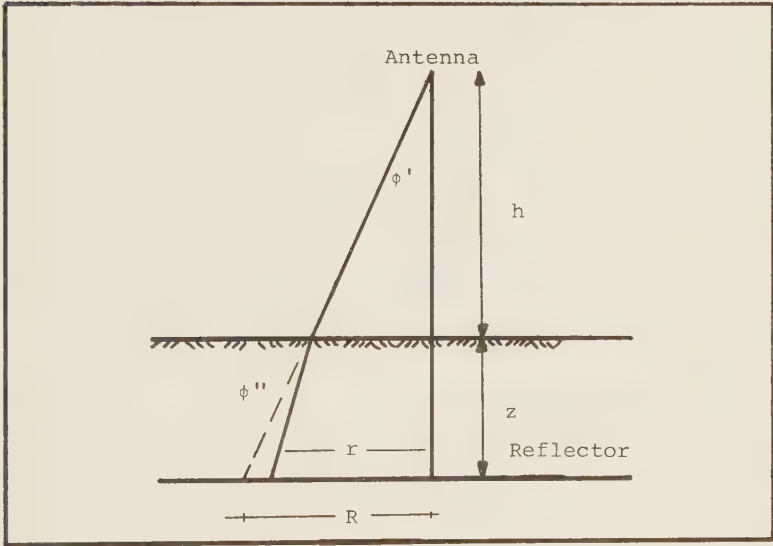


Figure 1.1. Elevated antenna. [From GUDMANDSEN 1972]

$$\frac{R}{r} = \frac{h/z + 1}{h/z + \tan \phi'' / \tan \phi'} \quad (1.55)$$

$$G_R = 20 \log \left(\frac{R}{r} \right) \quad (1.56)$$

Since the antenna is considered a point source this effect will also occur when the antenna is lying directly on the surface of the ground as pointed out by ELLERBRUCH 1974 although the same formula will not be valid.

The antenna gain is proportional to the effective area divided by the wave length. If the antenna is embedded in a material with a lower relative permittivity, the gain will increase, see (1.50).

Signal Processing

From a signal processing standpoint there is a wide similarity between impulse radar measurements and reflection seismics. The required processes are available for large scale computers and they have been successfully adopted for enhancing radar data, ENSCO Inc 1976. There is one fundamental difference however in that most radar surveys are performed with the antenna working both as a transmitter and as a receiver, while in reflection seismics several transmission and receiving locations are used. Considering the low cost of radar surveys compared with the cost of reflection seismics it is not economical to process radar data the same way.

A few of the operations will be described to give an idea of the possibilities.

Background removal and removal of noise is performed by using

$$f_{bi}(n) = F_i(n) - a_i(n) \quad i = j \text{ to } j + N_a - 1 \quad (1.57)$$

where

$$a_i(n) = \frac{1}{N_a} \sum_{k=j}^{j+N_a-1} f_k(n) \quad (1.58)$$

$f_{bi}(n)$ = value of record n after background removal

$f_i(n)$ = registered value of record n

$a_i(n)$ = average noise level

N_a = number of records in the computed average

j = record number at which the computation of average is started.

An echo that is constant in time is removed with this algorithm. By changing parameters j and N_a the average can take several forms:

- a) global average - containing all records
- b) block average - containing a certain number of records
- c) forward, moving average - using forthcoming records when calculating $a_i(n)$
- d) backward, moving average - using previous records when calculating $a_i(n)$

Another process can be described as a decaying recursive filter over a variable number of records, GEOPHYSICAL SURVEY SYSTEMS Inc 1980.

$$A(n) = A(n-1) + (D - A(n-1))/\tau \quad (1.59)$$

where

$A(n)$ = new average

$A(n-1)$ = stored average

D = computed average of N scans

τ = filter time constant

Whitening is a process that enhances weak signals and attenuates white noise. It emphasizes the pulse return characteristics and de-emphasizes repetitive or oscillating returns. The algorithm is described by

$$f_{wi}(n) = F^{-1}(FW_i(m)) \quad i = 1 \text{ to } N \quad (1.60)$$

$$FW_i(m) = F_i(m) \cdot A_i(m) \quad (1.61)$$

$$A_i(m) = \left(\frac{a + \epsilon}{|F_i(m)| + \epsilon} \right)^c \quad (1.62)$$

where

$F_i(m)$ = Fourier spectrum of the return $F_i(n)$

$A_i(m)$ = whitening factor

$|F_i(m)|$ = absolute value of $F_i(m)$

a = maximum value of $|F_i(m)|$ or of the average of $|F_i(m)|$ over all the N records

ϵ, c = empirical constants

A similar technique is cepstrum filtering which is efficient for removing reverberations such as multiple reflections (echoes). The power cepstrum algorithm is described by RANDALL and HEE, 1981.

$$C_p(n) = F^{-1}(\log F(f(n))) \quad , \quad (1.63)$$

where

$C_p(n)$ = power cepstrum record

$f(n)$ = original record

$F(f(n))$ = Fourier spectra of the original record

F^{-1} = Inverse Fourier transform

The performance of this operator is described by Figure 1.2 which shows how echoes can be removed from a signal.

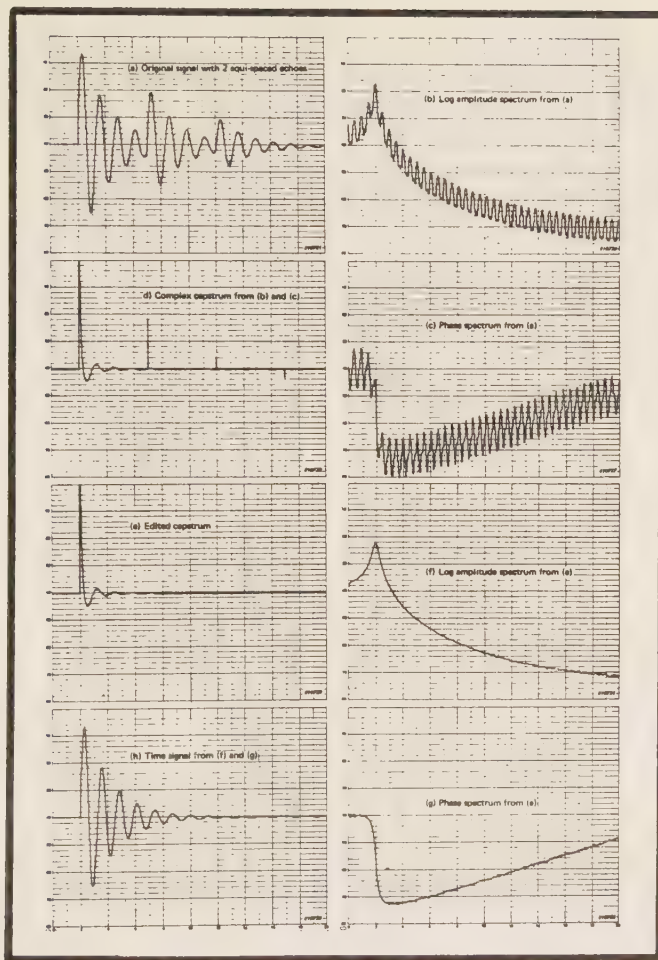


Figure 1.2. Echo removal using complex cepstrum [RANDALL and HEE 1981]

Velocity analysis can of course be done by drilling or digging which is a straightforward procedure in order to determine the depth and, from the measured reflection time, calculate the velocity.

A more sophisticated way to determine the velocity is the common depth point method which is used in reflection seismics. There are two requirements for this method to be

applicable: There must be a planar reflector extending for some distance along the profile and there must be two antennas, one transmitting and one receiving. The arrangement is described in Figure 1.3. By moving both antennas equal distances away from the initial center point the same reflection point will be maintained. The depth to the reflector can now be calculated using (1.64) where indices 1 and 2 refer to two different antenna separations x_1 and x_2 and corresponding signal delays t_1 and t_2 .

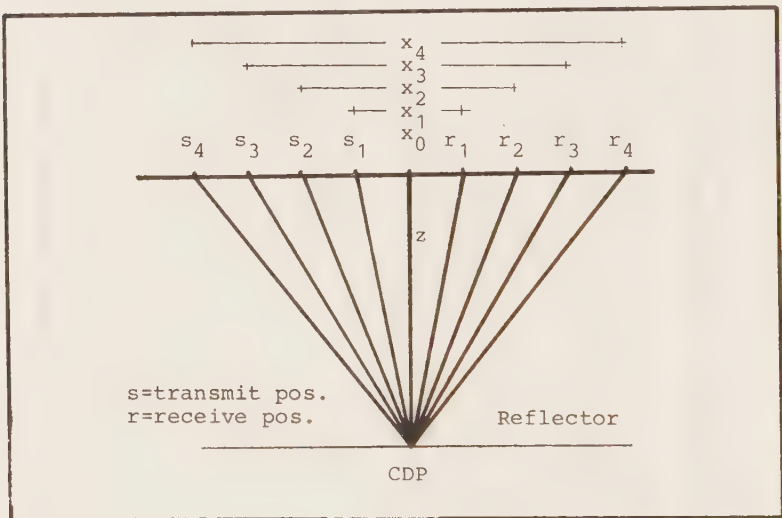


Figure 1.3. The common depth point method.

$$z = \sqrt{\frac{t_2^2 x_1^2 - t_1^2 x_2^2}{4(t_1^2 - t_2^2)}} \quad (1.64)$$

With the depth known the average velocity in the material is calculated using the delay when antenna separation was zero.

The other method is described in the Sir System Manual, by GSSI and requires only one antenna but a point target in the profiling plane. This can be a stone, a pipe or anything producing reflections that behave as if they originated from such a target. If the antenna moves across such

a target, buried at 0 in Figure 1.4 the distance s to the target will be a hyperbolic function of x and z according to (1.65).

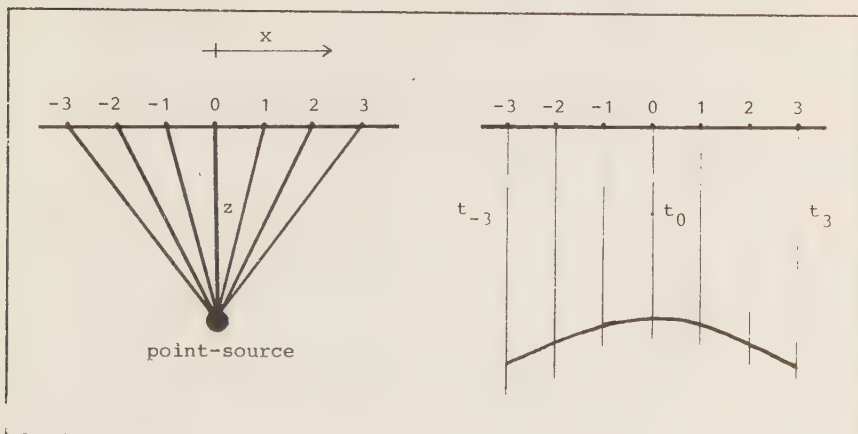


Figure 1.4. Velocity analysis from a point target.

$$s = \sqrt{x^2 + z^2} \quad (1.65)$$

Assume two positions x_0 and x where x_0 is at the vertex of the reflection in the diagram and at $x = 0$ in Figure 1.4. The corresponding distances z and s are proportional to the delay times t_0 and t . The depth to the reflector is calculated with

$$z = \frac{|x|}{\sqrt{\left(\frac{t}{t_0}\right)^2 - 1}} \quad (1.66)$$

and the average velocity v with

$$\bar{v} = \frac{z}{t_0} \quad (1.67)$$

The process of collecting all the energy of the hyperbolic tails in the vertex point is known as the migration operation or hyperbolic stacking. The radargram is thought of

as consisting of a number of scattering volumes. The algorithm is

$$f_i(t) = \sum_k a_{ik} \cdot g(t - T_{ik}) \quad (1.68)$$

where

$g(t)$ = the transmitted signal

a_{ik} = a complex coefficient representing transmission loss and scattering strength of the k :th unit scattering volume

$$h_i(t) = \sum_{m=-M}^M f_{i+m}(t + T_m) / \sum_{m=-M}^M f_{i+m}(t) \quad (1.69)$$

where

$$T_m = \frac{1}{c} [(x_i - x_{i+m})^2 + (ct)^2]^{\frac{1}{2}} \quad (1.70)$$

A way of enhancing signals at the cost of noise is the process called stacking which takes the running average for a number of subsequent radar transmissions for samples at equal time. In this way random signals will interfere destructively while persisting signals will be emphasized.

When the antenna moves on top of a volume containing a sloping planar reflector according to Figure 1.5 the resultant radargram will look like Figure 1.6.

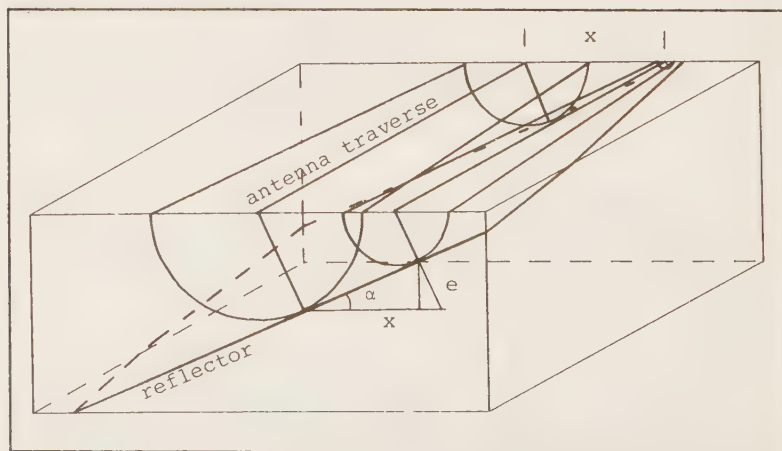


Figure 1.5. A volume with a reflecting plane tangent to a cone with the center line along the antenna traverse.

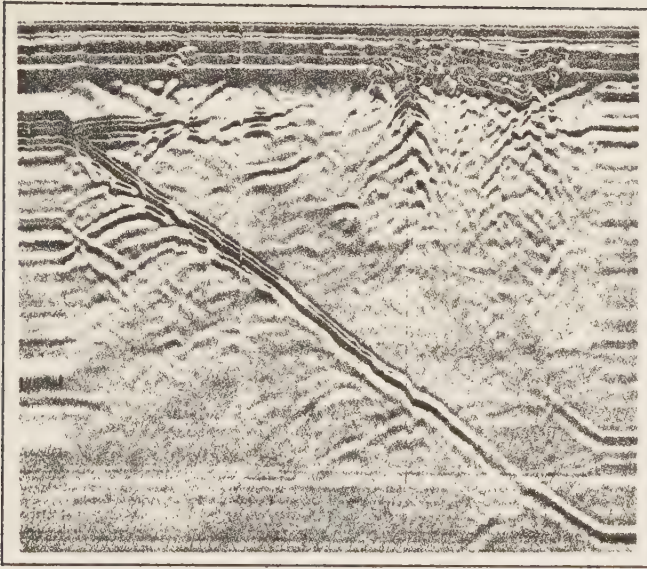


Figure 1.6. Radargram resulting from the example above.
 [From BJELM, FOLLIN and SVENSSON 1982.]

The registration tends to underestimate the depth to the reflector at every point, since the reflections come from a point "uphill" in which the normal to the reflector goes through the present antenna position.

If the measured angle in the radargram is ϕ_u the actual angle can be computed with the expression

$$\phi = \sin^{-1}(\tan \phi_u) \quad (1.71)$$

This angle defines the top angle of a cone with the center line along the radar traverse. The reflector plane lies tangent to the surface of the cone. If the normal to the reflector makes an angle α with the horizontal, the strike and dip of the reflector can be calculated according to

$$\text{Dip} = \tan^{-1}\left(\frac{\tan \phi}{\cos \alpha}\right) \quad (1.72)$$

$$\text{Strike} = \sin^{-1}(\cos \phi \sqrt{\cos^2 \alpha + \tan^2 \phi}) \quad (1.73)$$

The additional information needed to solve α is obtained by displacing the traverse a distance x so that a new, parallel traverse can be registered. This will give the elevation e of the reflector for the distance x and the angle α is calculated from

$$\alpha \approx \tan^{-1} \left(\frac{e}{x} \right) \quad (1.74)$$

Using the Fast Fourier Transform

As initially noted the Fast Fourier Transform (F) and its inverse (F^{-1}) are convenient ways to move from time domain $f(t)$ to frequency domain $F(\omega)$ and back again.

Assume that the propagation factor γ is a complex number $\gamma = \alpha + j\beta$ with α and β from (1.2) and (1.3). These quantities are frequency dependant $\alpha(\omega)$, $\beta(\omega)$. In order to calculate the shape of an initial impulse $f(t)$ just take its Fourier transform and multiply by the transfer function $H(\omega)$ containing $\alpha(\omega)$ and $\beta(\omega)$. Then take the inverse Fourier transform of the product and the result is the shape of the impulse at a distance z , NILSSON 1978.

$$F(f(t,0)) = F(\omega) = R(\omega) + I(\omega) \quad (1.75)$$

$$F(\omega) \cdot H(\omega) = e^{-\alpha(\omega)z} [\cos(\beta(\omega) \cdot z) \cdot R(\omega) - j \sin(\beta(\omega) \cdot z) \cdot I(\omega)] \quad (1.76)$$

$$f(t,z) = F^{-1} [H(\omega) \cdot F(\omega)] \quad (1.77)$$

If the problem is a reflection the same method applies for $f(t)_R$ the reflected wave

$$f(t)_R = F^{-1} [R(\omega) \cdot F(\omega)] \quad (1.78)$$

where $R(\omega)$ is calculated from the complex impedances according to (1.10).

In detail the FFT algorithm used requires 2^N samples where N is an integer. The algorithm produces 2^{N-1} real $R_1(\omega)$

and 2^{N-1} imaginary $I1(\omega)$ components. The magnitude, $M(\omega)$ of each frequency component is the magnitude of the associated complex number $R1 + jI1$.

$$M(\omega) = \sqrt{R1(\omega)^2 + I1(\omega)^2} \quad (1.79)$$

The phase $\theta(\omega)$ is calculated according to

$$\theta(\omega) = \tan^{-1} \frac{I1(\omega)}{R1(\omega)} \quad (1.80)$$

where the actual phase angle is determined from the sign of $I1(\omega)$ and $R1(\omega)$ according to the Argand diagram, Figure 1.7.

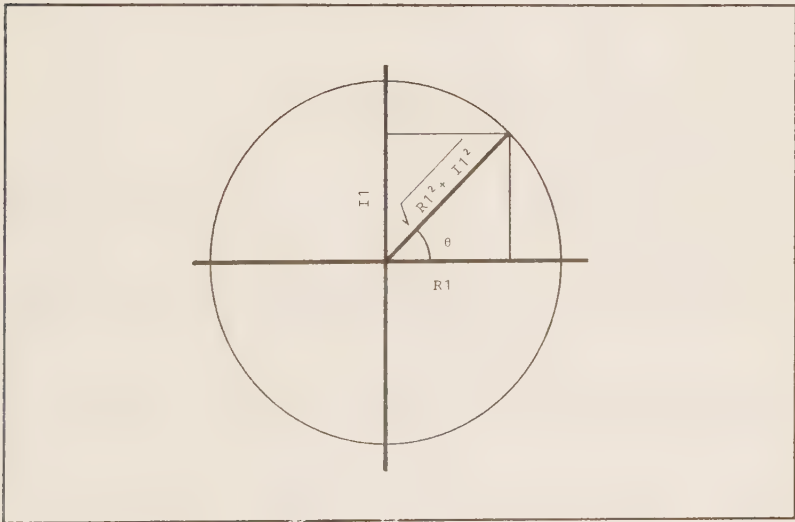


Figure 1.7. Argand diagram showing the components $R1$, $I1$ and phase θ .

Permittivity and Conductivity of Soil, Rock and Water

Strictly speaking ϵ and σ are frequency dependant and it is therefore favourable to express them as complex numbers, KING and SMITH 1981.

$$\epsilon = \epsilon' - j\epsilon'' \quad (1.81)$$

where

ϵ' = real part

ϵ'' = imaginary part

and the complex conductivity

$$\sigma = \sigma' - j\sigma'' \quad (1.82)$$

An examination of Maxwell's equations and the associated boundary conditions reveals that ϵ and σ always appear in the combination

$$\sigma + j\omega\epsilon = \sigma' + \omega\epsilon' + j\omega(\epsilon' - \frac{\sigma''}{\omega}) \equiv \sigma_e + j\omega\epsilon_e \quad (1.83)$$

where

σ_e = the real effective conductivity

ϵ_e = the real effective permittivity

$$\sigma_e \equiv \sigma' + \omega\epsilon'' \quad (1.84)$$

$$\epsilon_e \equiv \epsilon' + \frac{\sigma''}{\omega} \quad (1.85)$$

Whenever σ and ϵ are encountered as real numbers in this thesis it is these parameters that are referred to.

The schematic variation of ϵ'_r and ϵ''_r with frequency is presented in Figure 1.8.

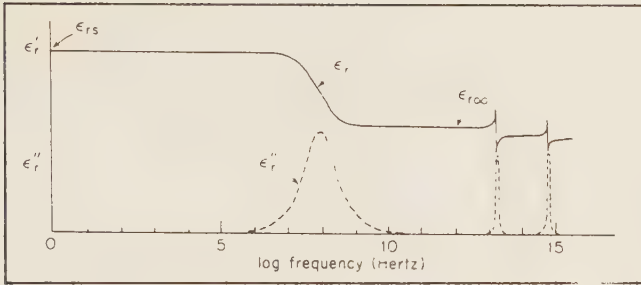


Figure 1.8. Schematic variation of ϵ'_r and ϵ''_r with frequency. [King and Smith 1981]

Rocks are complex materials composed of many different minerals in widely varying proportions. Most rocks contain moisture, usually with some measure of salinity. Since the relative permittivity of water is 81 even small amounts of water may increase the relative permittivity of the rock. Typical changes of ϵ_r with moisture content is given in Figure 1.9.

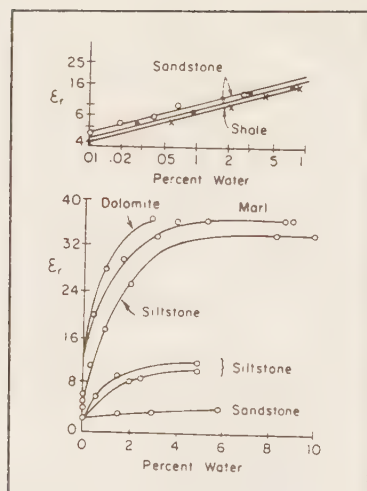


Figure 1.9. Effect of moisture content of rock on permittivity [KING and SMITH 1981].

The conductivity varies in a much wider range, about twenty orders of magnitude. Not only is the rock type important but also the amount of water. The conductivity of sandstone has been reported to be $7 \cdot 10^{-6}$ mho/m when wet and $1.5 \cdot 10^{-9}$ mho/m when dry. Generally materials with $\sigma_e < 10^{-7}$ mho/m are considered isolators and those with $\sigma_e > 10^5$ mho/m are considered conductors. Materials with intermediate values of σ_e belong to the category semiconductors.

Soil is also a mixture of many components, where both permittivity and conductivity depend on water content. Thus dry sand and soil may have relative permittivities ranging from 2 to 6 and conductivities between 10^{-4} to 10^{-5} mho/m. Wet soil may have relative permittivities in the order of 5 to 15 with conductivities ranging from 10^{-2} to 10^{-3} mho/m.

Thus water has a strong influence on the properties of rock and soil. For many applications the real effective permittivity and conductivity of water may be assumed to be

$$\epsilon_e = \epsilon' \quad (1.86)$$

$$\sigma_e = \sigma_0 + \omega\epsilon'' \quad (1.87)$$

where σ_0 is the DC conductivity and ϵ' and ϵ'' are obtained from the Debye formula

$$\epsilon = \epsilon' - j\epsilon'' = \epsilon_\infty + \frac{\epsilon_s - \epsilon_\infty}{1 + j\omega\tau} \quad (1.88)$$

where

ϵ_∞ = high frequency permittivity

ϵ_s = low frequency permittivity

τ = relaxation time of water

The variation of ϵ' and ϵ'' for water is presented as a function of frequency in Figure 1.10.

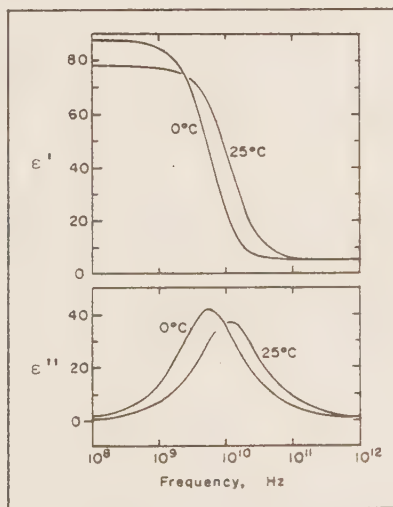


Figure 1.10. The dielectric relaxation spectrum of water at two temperatures [HOEKSTRA and DELANEY 1974].

For a clay-loam soil with 10 % water content by weight, the variation of relative effective permittivity and effective conductivity with frequency is presented in Figure 1.11.

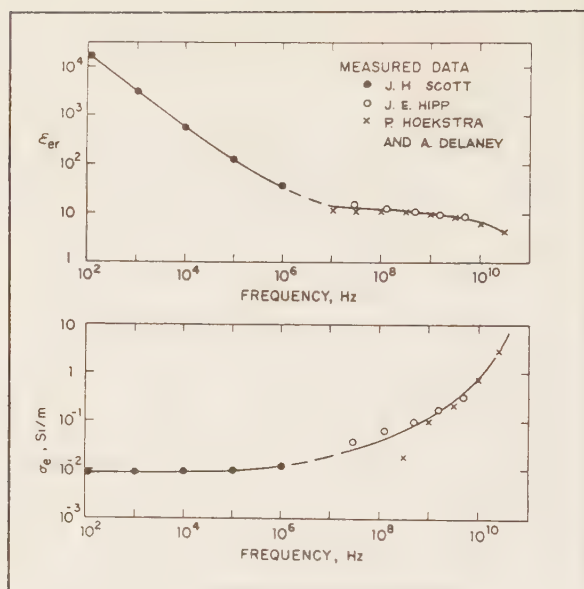


Figure 1.11. Variation of ϵ_{er} and σ_e with frequency for a clay-loam soil with 10 % water content by weight.

An illustration of how conductivity can vary with moisture content for a silty clay at $2 \cdot 10^5$ Hz is presented in Figure 1.12.

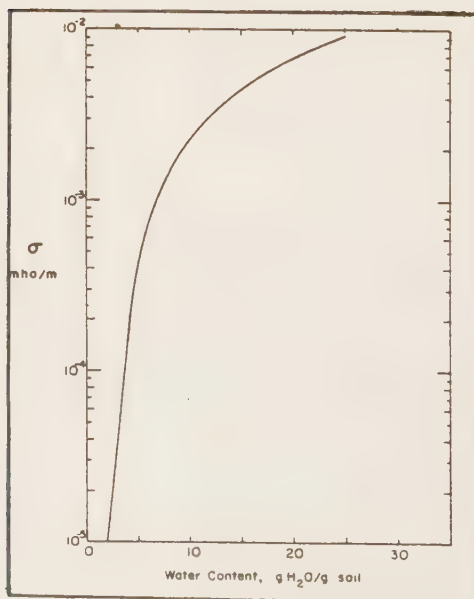


Figure 1.12. The conductivity of a silty clay as a function of water content measured at $2 \cdot 10^5$ Hz [SMITH - ROSE 1933].

In Table 1.1 is a presentation of effective values of ϵ_r and σ for a number of materials, wet and dry, that are likely to be encountered in radar surveys.

Table 1.1. Approximate values of σ and ϵ_r for a variety of materials.

Material	σ mho/m	ϵ_r
Air	0	1
Pure water	10^{-4} to $3 \cdot 10^{-2}$	81
Seawater	4	81
Freshwater ice	10^{-3}	4
Granite (dry)	10^{-8}	5
Limestone (dry)	10^{-9}	7
Clay (saturated)	10^{-1} to 1	8 to 12 ;
Snow firn	10^{-6} to 10^{-5}	1.4
Sand (dry)	10^{-7} to 10^{-3}	4 to 6
Sand (saturated)	10^{-4} to 10^{-2}	30
Silt (saturated)	10^{-3} to 10^{-2}	10
Seawater ice	10^{-2} to 10^{-1}	4 to 8
Basalt (wet)	10^{-2}	8
Granite (wet)	10^{-3}	7
Shale (wet)	10^{-1}	7
Sandstone (wet)	$4 \cdot 10^{-2}$	6
Limestone (wet)	$2.5 \cdot 10^{-2}$	8
Copper	$5.8 \cdot 10^7$	1
Iron	10^8	1
Soil - sandy dry	$1.4 \cdot 10^{-4}$	2.6
- sandy wet	$6.9 \cdot 10^{-3}$	25
- loamy dry	$1.1 \cdot 10^{-4}$	2.5
- loamy wet	$2.1 \cdot 10^{-2}$	19
- clayey dry	$2.7 \cdot 10^{-4}$	2.4
- clayey wet	$5.0 \cdot 10^{-2}$	15
Permafrost	10^{-5} to 10^{-2}	4 to 8

Data from MOREY 1974, KELLER 1966, VON HIPPEL 1954.

Articles not listed.

2 MEASUREMENTS IN SOIL, BEDROCK AND WATER

Previous work and some principles

A historical review of the development of subsurface radar profiling is given in NILSSON 1978, which includes more than 100 references. The distribution in time of these references is given in Figure 2.1.

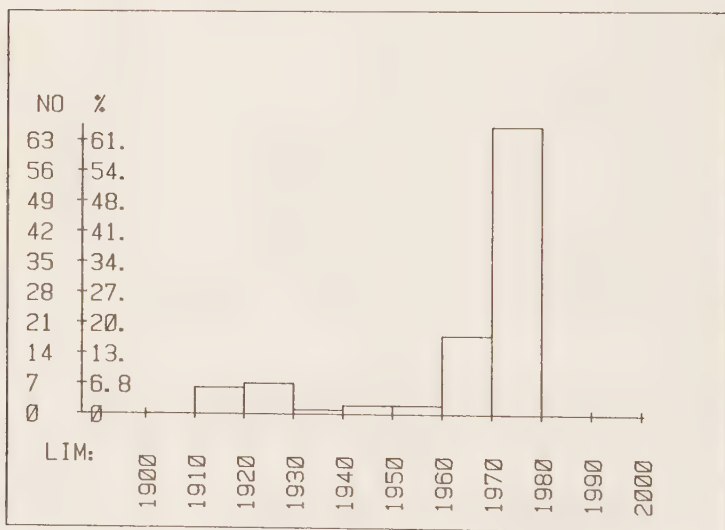


Figure 2.1. Distribution in time of the references cited in NILSSON 1978.

A similar plot of the seventies with the articles found by the author included is presented in Figure 2.2. The 1974 peak is associated with theoretical papers and feasibility studies. The Apollo 17 Lunar sounder experiment in the early seventies caused many articles to be written. The articles published in the early eighties often deal with practical application of the technology. Many articles concern measurements in coal seams.

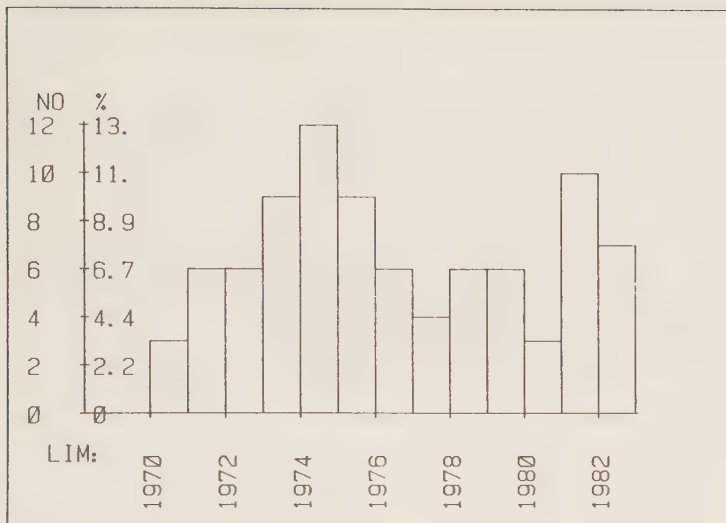


Figure 2.2. Distribution in time of the references of NILSSON 1977 and the author for the seventies and early eighties.

This presentation only concerns the work of the author and reference is given to related publications. There is no pretention to present the entire field of radar profiling in soil and bedrock.

In the profiling mode the impulse radar works as an echo sounder with a similar graphical display. The difference is that there is no need for the radar antenna to be in physical contact with the medium and that for equal wavelengths there is considerably less attenuation of electromagnetic energy than of mechanical energy.

In order to transform the two way reflection times into distance the velocity must be known. Methods for this is described under the section "Signal Processing". The power of radar profiling is increased if the material shows a homogenous velocity distribution.

The main problem is the ground water table, since it changes the relative permittivity of most soils by a factor 5-6. This fact also makes it a good reflector if it is associated with a steep change in the soil's water content as seen in coarse material. In unsorted soils such as moraine there will be a broad and varying capillary zone and thus no clear reflection. For the frequencies used it has been discovered that it is possible to detect the ground water table in coarse sand but not in finer material.

The water table also produces refraction gain and increases the resolution. If the antenna lies directly on a soil of uniform moisture, the antenna gain will increase in proportion to the water content. Both effects can not occur in the same situation.

The soil may contain a great number of scatterers in the upper layer which makes the profiles difficult to interpret. To overcome this two separated antennas are used - bistatic radar profiling. One antenna is used as a transmitter and the other as a receiver and near surface echoes will be returned to the transmitter-rather than to the receiver-antenna. Echoes from large depths will thus be enhanced at the cost of near-surface echoes.

Profiling in Sand and Gravel

In Figure 2.3 is a presentation of the first successful radar profile that was carried out by the author. The profile is situated at the north side of the island Fårö in the Baltic Sea. The profile length is about 50 m and the depth to the bedrock, consisting of limestone varies between 4 and 5 m. The ground water table is not visible but observed at ~ 1.5 m depth in a nearby water well. The diagram shows the unique capacity of the radar to display the stratification of soils. This gives the trained operator possibilities to derive the soil type from knowledge of how it was deposited.



Figure 2.3. Radar profile through sand at Fårö in the Baltic Sea. [BJELM, BRUCH and ULRIKSEN, unpublished]

A few hundred meters south of the profile the national park Ullahau is situated. There are large formations of wind-blown sand. The sea lies about 100 m in the left direction of the profile.

The interpretation of the diagram is that on the limestone lies sand which is deposited in the beach-zone (note the bedding planes). On top of this a layer of wind-blown sand characterized by some disorder. The depth scale is discontinuous due to the presence of the ground water table. By using data from Table 1.1 the relative permittivity of the unsaturated sand is assumed ~ 6 and of the saturated sand ~ 30 . When passing the ground water table the scale changes in proportion to the difference in radio-wave velocities, resulting in the depth scale to the right of the diagram. This simple method is only possible because of the flat and horizontal surface of the ground along the profile. It is of interest to note, in the central part of the profile,

the point-source reflector which lies in the lower part of the area interpreted as wind-blown sand. This reflector can be a log or a stump.

In Figure 2.4 an esker buried in a delta is located. The profile is situated at Tärnsjö in Uppland. Note how the slopes of the esker interfere at sharp angles with a horizontal reflection. Only the ground water table can cross a layer interface and that determines the origin of the horizontal reflector. To the left in the profile is the coarse grained core of the esker.

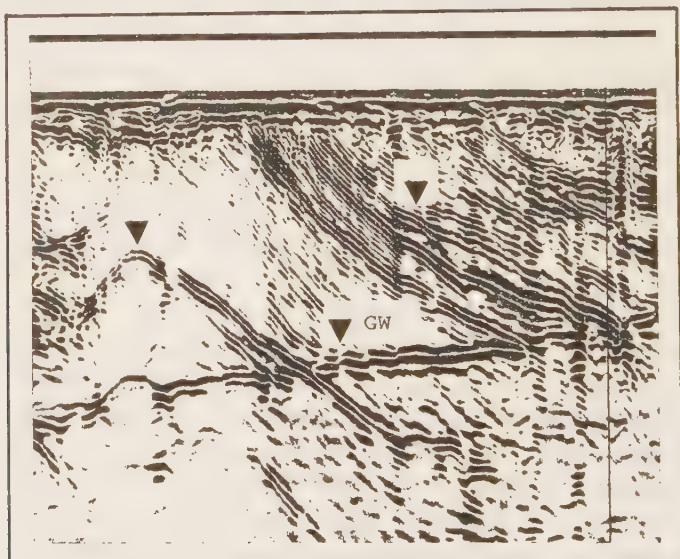


Figure 2.4. Location of an esker buried in a delta at Tärnsjö in Uppland. [BJELM, FOLLIN and SVENSSON 1982.]

Sand and gravel are the soils that give the best radar penetration. An example of this is given in Figure 2.5 which shows the layers of a delta with a sloping ground water table. The profile is situated at Sörmon in Värmland. With the help of previously used relative permittivities of the

sand, the unsaturated layer is calculated to have a thickness of 6.1 m and the last return is located 14.2 m below the ground surface.

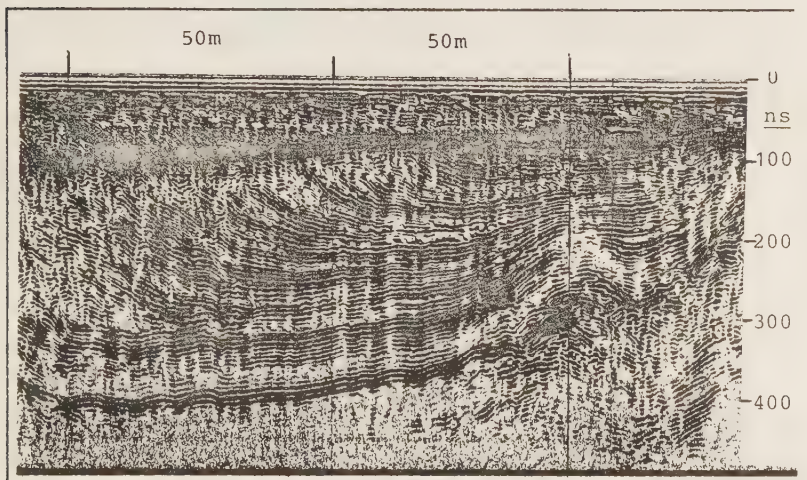


Figure 2.5. Delta layering and ground water table at Sörmon in Värmland. [BJELM, FOLLIN and SVENSSON 1982.]

In Figure 2.6 a profile in sand with pebbles or boulders, lying on boulder clay is presented. The profile is situated at Södra Sandby in Skåne. All the small hyperbolas are caused by pebbles or boulders.

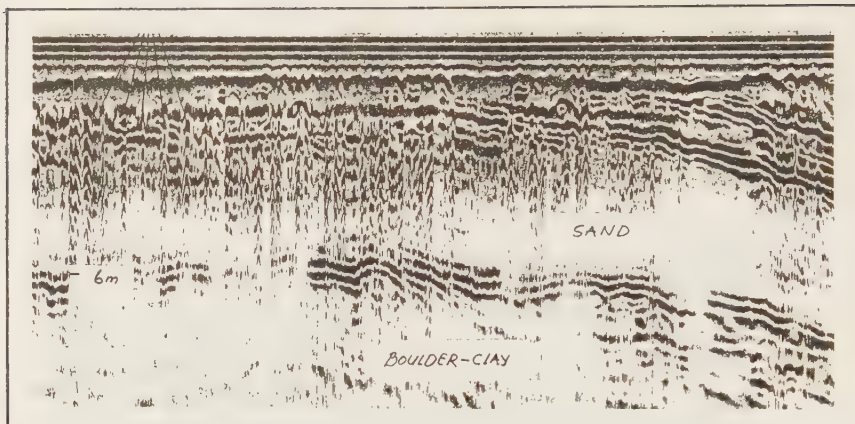


Figure 2.6. Sand containing pebbles and boulders. Södra Sandby in Skåne. [ULRIKSEN 1982]

Profiling in Peat

The most successful soil radar measurements are performed in peat as shown by ULRIKSEN 1979, 1980, 1982, BJELM 1980 and BJELM and ULRIKSEN 1980.

As peat decomposes the water content decreases PÄIVANEN 1973. According to the method by VON POST 1922, 1926, the decomposition of peat, is measured against a 10 degree scale where 1 is a practically undecomposed peat and 10 is a fully decomposed peat. From this it can be concluded that the relative permittivity of peat varies proportional to the degree of decomposition or humification as it is also called. Henceforward the term humification is used.

In combination with the CDP-method this would give a possibility not only to determine the thickness of the peat but also the degree of humification.

The first field test at a virginal peat bog was conducted in November 1979 at Stormyran in Västerbotten. A profile 1400 m long had been surveyed by conventional methods. The radar equipment was mounted in a tracked vehicle with the antenna towed behind on a sled. In 20 minutes the peat thickness was continuously determined along the entire profile except for about 50 m where the peat thickness was greater than ~ 10 m. The result is presented in Table 2.1.

Table 2.1. Results from radar profiling at Stormyran, 120 MHz antenna. [ULRIKSEN 1979.]

Location	z	$\bar{H}$	twt	$\bar{v}$	$\bar{\epsilon}_r$	z^*	Δz
0/100	4.30	5.8	234	0.37	67	4.44	-0.14
0/200	3.10	4.8	150	0.41	53	3.01	0.09
0/300	2.50	5.0	114	0.44	47	2.40	0.10
0/400	4.10	4.2	196	0.42	51	3.79	0.31
0/500	3.10	4.3	158	0.39	58	3.15	-0.05
0/600	4.60	5.2	264	0.35	74	4.95	-0.35
0/700	4.40	5.6	228	0.39	60	4.33	0.07
0/800	6.70	5.4	354	0.38	63	6.47	0.23
0/900	>7.5	-	382	-	-	6.95	
1/000	>7.5	-	402	-	-	7.29	
1/100	>7.5	-	538	-	-	9.60	
1/200	5.20	5.2	292	0.36	71	5.42	-0.22
1/300	3.70	4.9	182	0.41	54	3.55	0.15
1/400	1.50	4.7	74	0.41	55	1.72	-0.22
1/500	2.90	5.1	142	0.41	54	2.87	0.03

z = sampled thickness
 $\bar{H}$ = average degree of humification
 twt = two way reflection time
 $\bar{v}$ = average velocity ($2 z/\text{twt}$)
 $\bar{\epsilon}_r$ = average relative permittivity

At 0/900 - 1/100 the sampling was aborted at 7.5 m
 z^* = estimated thickness
 Δ = residual values

A linear regression of z and twt gives the relation

$$z^* = 0.46 + 0.017 \cdot twt \quad (2.1)$$

the correlation coefficient r is 0.99.

The constant term is attributed to a lower water content in the vegetation layer at the surface of the peat bog.

To check if the relative permittivity is a measure of the degree of humification another regression was performed for $\bar{H}$ and $\bar{\epsilon}_r$. By using linear, exponential, logarithmic and power regression the correlation coefficient r was never greater than 0.54. Consequently this data does not show any possibility in determining the degree of humification from the relative permittivities.

In Figure 2.7 is a presentation of a part of the radar profile. To the right of the subsurface hill is a point-source reflection, which is believed to be a stump. It is evident that most obstacles can be located and hence avoided when the peat bog is explored.

If the radar method cannot provide data about the humification of a peat layer it can outline the interfaces between layers where the degree of humification varies, BJELM 1980. In order to do this it is essential that there is a rather sharp contrast between the degree of decomposition of the layers. (2-3 units in the VON POST-method meet this requirement.)

The radar also yields information concerning the soil lying under the peat. If till lies under the peat there will be a large amount of scattering due to the boulders in it and if it is clay there will be a strong return due to the high conductivity of the clay. No energy should be transmitted through the clay, so signals appearing after the clay surface return can be considered system noise. If the clay layer is very thin some energy may pass through

it. In Figure 2.7 this interpretation technique locates till at the top of the hill and clay in the bay to the left.

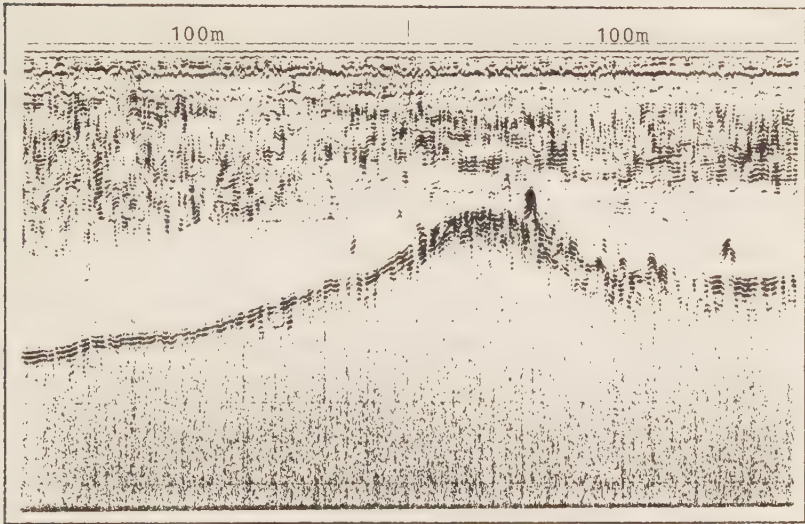


Figure 2.7. Part of radar profile at Stormyran. |ULRIKSEN 1979. |

The next object of study was 10 different peat bogs in the vicinity of Strömsund in Jämtland, SKANRAD AB 1981. The entire area was surveyed from helicopter to choose objects suited for radar surveys, i.e. no dense vegetation or deep cutting ditches. Following this, 50 km of peat profile was recorded in 4 days time. The survey was performed in April and the ground was covered with a half-meter thick layer of melting snow. The amount of signal loss was negligible. In Table 2.2 is a presentation of the reference points used and the associated return delays, twt.

A linear regression of z and twt yields a relation in the form

$$z^* = 0.144 + 0.018 \cdot twt \quad (2.2)$$

the correlation coefficient is 1.0.

In this case the constant term is smaller which perhaps depends on the wet snow at the surface of the peat bog. Also another antenna was used. This survey was made with a few profiles over each project. A typical profile layout is presented in Figure 2.8.

Table 2.2. Results from radar profiling at 10 peat bogs near Strömsund, 80 MHz antenna. |SKANRAD AB 1981.|

z	twt	$\bar{v}$	ϵ_r	z^*	Δz
2.50	124	0.40	56	2.40	0.10
3.10	154	0.40	56	2.95	0.15
2.60	134	0.39	59	2.59	0.01
2.20	118	0.37	66	2.30	-0.10
0.70	30	0.46	43	0.69	0.01
1.50	82	0.37	66	1.64	-0.14
3.20	166	0.39	59	3.17	0.03
1.70	82	0.41	54	1.64	0.06
1.80	92	0.39	59	1.82	-0.02
3.50	186	0.38	62	3.54	-0.04
3.20	180	0.36	69	3.43	-0.23
2.50	124	0.40	56	2.40	0.10
2.80	144	0.39	59	2.77	0.03
1.20	56	0.43	49	1.16	0.04
1.50	78	0.38	62	1.57	-0.07
3.60	186	0.39	59	3.54	0.06

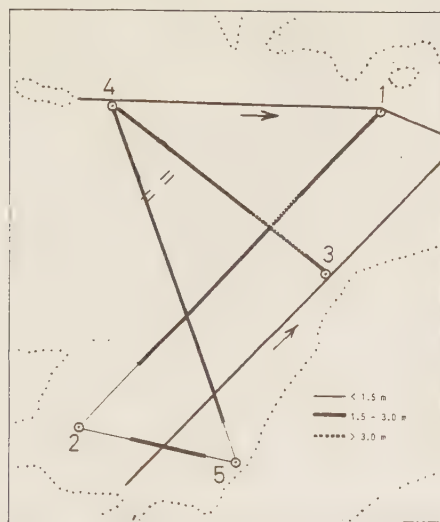


Figure 2.8. Typical profile layout for the survey in the vicinity of Strömsund combined with thickness presentation. |SKANRAD AB 1981.|

Following this a detailed survey of Dala Mosse in Småland was performed, ULRIKSEN 1982. Parallel profiles in E-W direction covered the area together with two profiles in N-S direction. The length of the profiles varies between 1 and 2 km. In a small area of 200 x 200 m parallel profiles at 20 m separation were recorded. There were a few small "islands" in this part of Dala Mosse. Profiles were recorded around and between them to study the morphology of their bases. The entire system is presented in Figure 2.9.

Along profile A the peat thickness was determined and the result of this was compared with the radar return delays. This is presented in Table 2.3. The last value in this table is in error. The sampling stopped at a stump or some other object. This can be concluded because the calculated relative permittivity is greater than for pure water $\epsilon_r = 81$. This shows one aspect of the superiority of the radar method. The sampling was stopped about 1 m above the bottom of the peat bog.

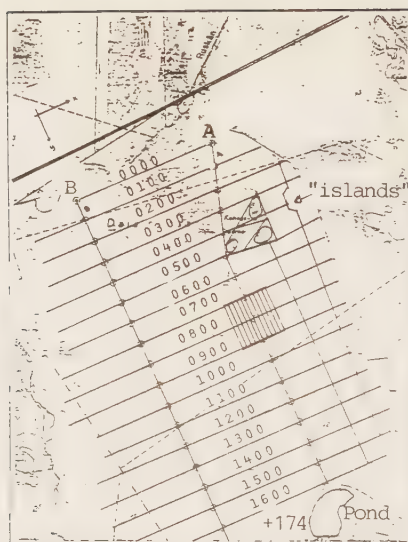


Figure 2.9. The profile pattern developed at Dala Mosse.
|ULRIKSEN 1982.|

Table 2.3. Results from radar profiling at Dala Mosse, 80
MHz antenna. |ULRIKSEN 1982.|

z	twt	$\bar{v}$	$\bar{\epsilon}_r$	z^*	Δz
4.40	245	0.36	69	4.37	0.03
3.60	210	0.34	77	3.76	-0.16
3.80	210	0.36	69	3.76	0.04
5.00	270	0.37	66	4.81	0.19
5.50	300	0.37	66	5.33	0.17
4.70	275	0.34	77	4.90	-0.20
6.50	345	0.38	62	6.12	0.38
6.50	350	0.37	66	6.20	0.30
6.50	350	0.37	66	6.20	0.30
6.20	350	0.35	73	6.20	0.00
7.30	405	0.36	69	7.16	0.14
5.20 ¹	360	0.28 ¹	114 ¹	6.38	-1.18

¹ erroneous results

The usual linear regression, when the erroneous sampling has been eliminated, gives

$$z^* = -0.295 + 0.19 x \quad (2.3)$$

the correlation coefficient is 0.99. Here the constant term is negative. The antenna used was the same one as used at Strömsund and the results should be comparable. The probable explanation for this negative term is that the 80 MHz antenna gives a negative constant term and this is compensated for by the wet snow, which creates a delay. In Figure 2.10 is an ensemble of all the predicted peat thicknesses as a function of the actual measured values.

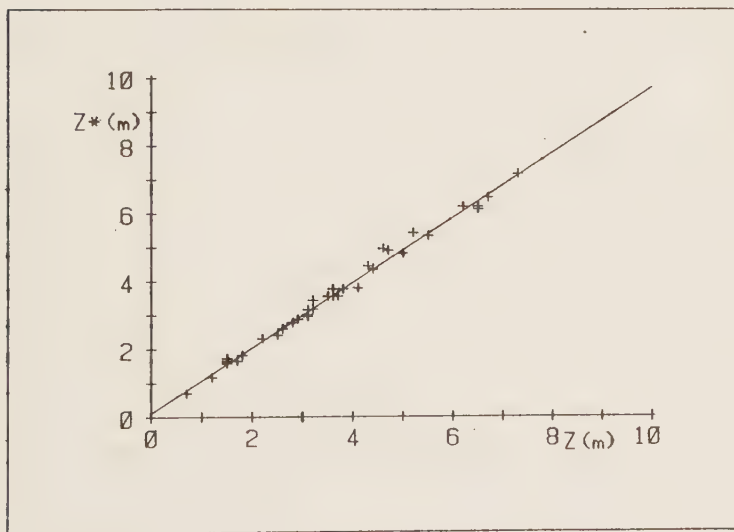


Figure 2.10. Predicted z^* thickness values compared to the actually measured values from 12 Swedish peat bogs.

The agreement is excellent and it may be concluded that the radar method yields more trust-worthy data than a conventional sampling of the peat thickness. This is a method that is so accurate that there is no adequate means to measure its quality.

It is interesting to note that the first order term in 2.1-3 has the values 0.017, 0.018 and 0.019. This factor is half of the average velocity measured in m/ns. We may conclude that as we move from Umeå to Värnamo the radio-wave velocity shows a slight increase. This may be due to the fact that peat bogs in southern Sweden have a higher average degree of humification than the northern ones. The more humified the peat the less water it contains and consequently the velocity will increase.

In order to see if the peat thickness explains the variance in relative permittivity these parameters are plotted against each other in Figure 2.11.

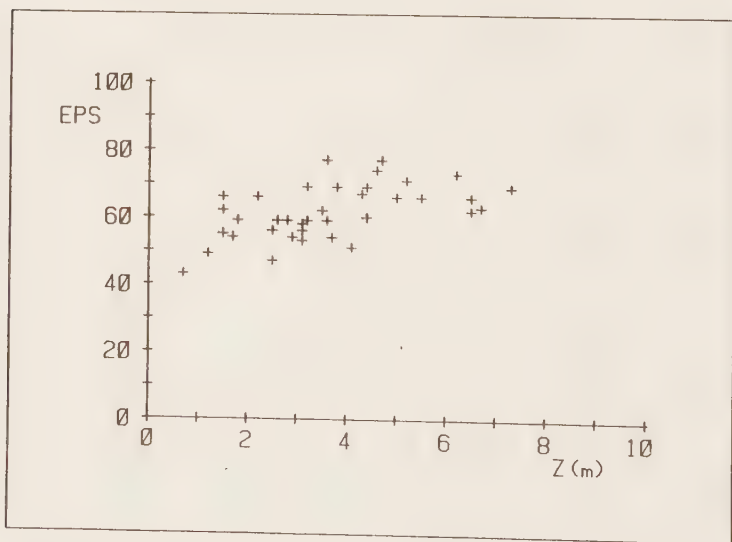


Figure 2.11. Relative permittivity as a function of peat thickness.

The relation is very weak with a tendency for the relative permittivity to increase with peat thickness. Due to the weakness of the relation this effect is not further considered.

Presentation of Peat Surveys

The radar data may be presented as profiles or maps.
The west N-S directed profile is presented in Figure 2.12.

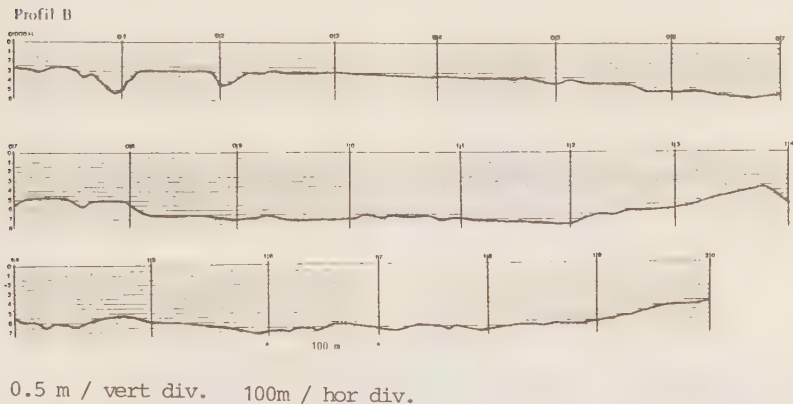


Figure 2.12. Presentation of peat profile B. | ULRIKSEN 1982. |

In order to present the entire material of this survey the color jet plotter developed by scientists from Lund was used. The profiles were digitized in extreme points between 50 and 75 m in distance. This was done manually resulting in 441 digitized thickness values. The data program interpolates 6000 values evenly distributed over the area. It also has the interesting feature of calculating data statistics as presented in Table 2.4. For every given class, the program calculates the percentage of the area where the value of the peat thickness falls between the class limits. This makes it possible to determine the peat thickness distribution as in Figure 2.13.

Table 2.4. Distribution of peat thickness in areal percentage. |ULRIKSEN 1982. |

CLASS LIMITS	COLOR CODES	PERCENTAGE
- .300000+001	161616	.01
- .700000+001	1616	.54
- .750000+001	1612	3.40
- .700000+001	1608	17.93
- .650000+001	1604	11.32
- .600000+001	1600	9.81
- .550000+001	161600	9.74
- .500000+001	161200	11.23
- .450000+001	160800	16.43
- .400000+001	160400	7.37
- .350000+001	160414	4.02
- .300000+001	160012	1.41
- .250000+001	160008	.50
- .200000+001	160004	.16
- .150000+001	160000	.15
- .100000+001	120000	.12
- .050000+000	000000	.00
- .000000	400000	.00
PERCENTAGE OF UNDEFINED AREA: 7.26		
UNDEFINED VALUE: 99.000		
COLOR CODE FOR UNDEFINED AREA: 0		
GEOPAK HAS NOW GENERATED A CONTOUR MAP		

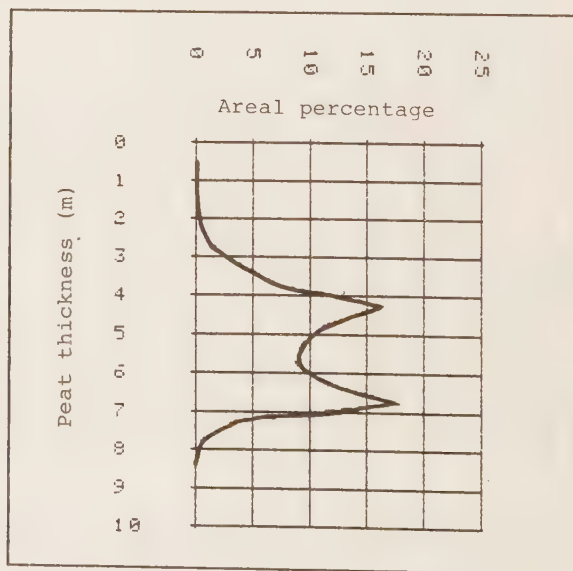


Figure 2.13. Graphical presentation of the data in Table 2.4. |ULRIKSEN 1982. |

RADARSONDERING DALA MOSSE

LEGEND

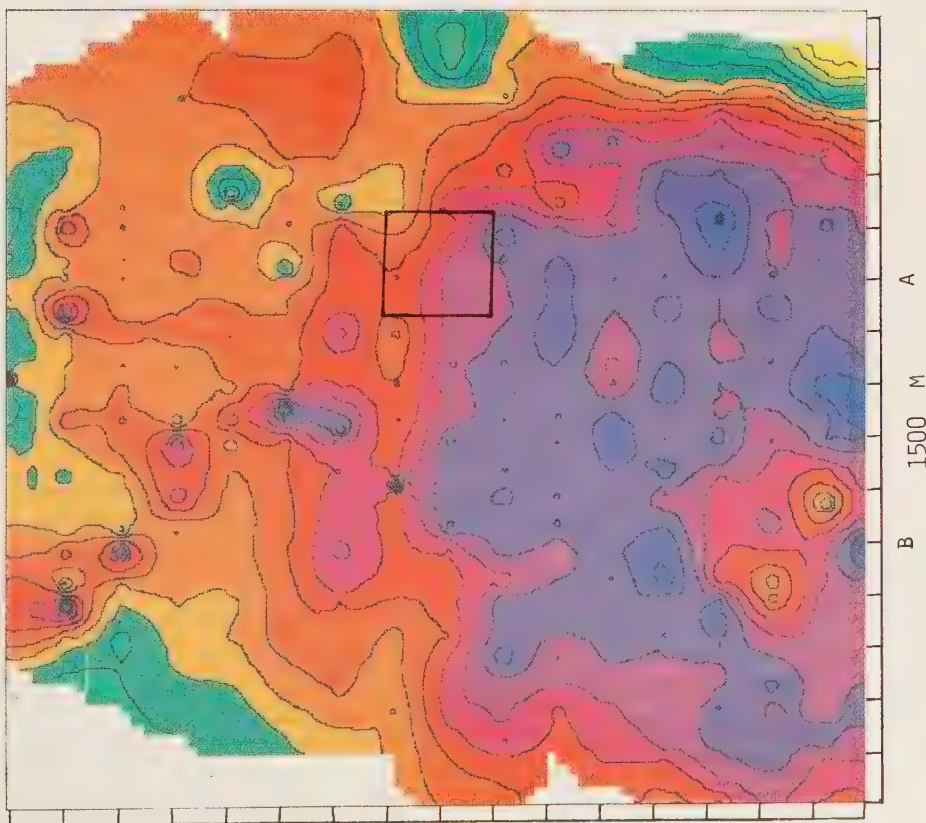


Figure 2.14 Color Jet Plotter presentation of peat thickness measured with radar.

From the two peaks one can assume that there are two main levels in this peat bog, which is also shown by the color jet plotter output in Figure 2.14. There is a deeper southern part of the peat bog, which probably was a former lake. Figure 2.14 also shows two prehistoric islands that have been situated in the southern part of the lake. This can be concluded since the depths to them are less than the depth to the upper part of the threshold. In the northwestern part of the map a previous z-shaped river outlet is pictured. Due to the interpolation algorithm and the relatively distant input values the true continuation of this riverbed is not evident. It is displayed as series of deep holes located where the profiles cross it.

In Figure 2.15 is a presentation of the 5 profiles around the little "islands" in the northeastern part of the peat bog. Here the radar shows its unique quality as a structural informer. The islands consists of till surrounded by sand which lies under the peat.

The radar records have a compressed x-axis, which makes them look more dramatic than the recorded structures actually are. This is explained by Figure 2.16 which is a comparison between the real time radargram and the recorded structure as it appears when the x- and y-axis have the same scale. The radargram also illustrates that the radar cannot record more than a certain amount of slope. If the slope exceeds this value the radar return will not return to the antenna but will be lost. The structure is the previously mentioned riverbed in the northwestern part of the map in Figure 2.14.

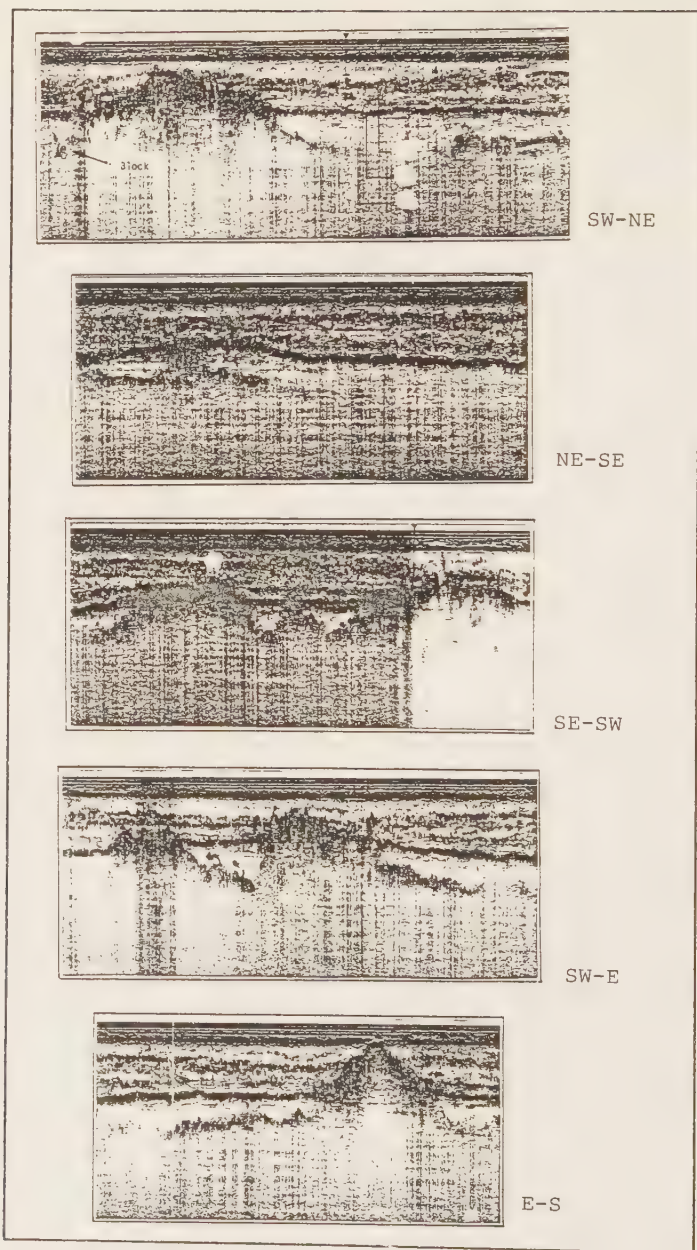


Figure 2.15. The five profiles surrounding and intersecting the "islands" at Dala Mosse. [ULRIKSEN 1982.]
(Original radar records of bad quality)

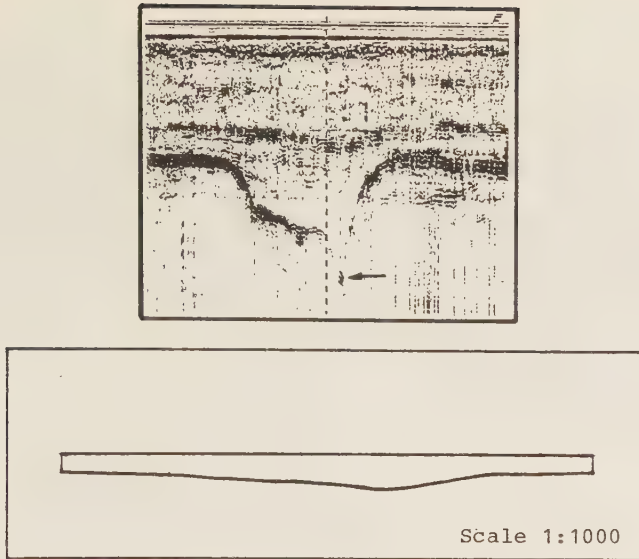


Figure 2.16. Comparison of a real time radargram and the actual structure. [ULRIKSEN 1982.]

The maximum recordable slope is identical to the radiation angle of the antenna. This is not a fixed measure but rather a matter of detection level in the receiver. For practical purposes though it is regarded as an angle. In order to determine the radiation angle for the 80 MHz antenna in peat, the geometry of 10 point-source reflections was studied. From the calculated depth z and the horizontal distance x the reflections were visible, the apparent radiation angle α can be calculated. The angle α is measured from the vertical and data is presented in Table 2.5. The relation for calculating α is

$$\alpha = 2 \arctan g \left(\frac{x}{2 \cdot z} \right) \quad (2.4)$$

Table 2.5. Calculation of radiation angle α in peat from point-source reflections. Data from Stormyran. |ULRIKSEN 1982. |

Source	Depth z	Length x	Radiation angle α
1	2.92	3.32	39.2
2	2.69	2.72	37.3
3	2.06	3.02	36.0
4	2.93	3.93	40.06
5	2.37	2.11	34.1
6	1.89	2.72	34.4
7	2.61	1.82	33.5
8	2.29	1.81	32.2
9	3.48	3.62	40.5
10	<u>3.24</u>	<u>3.02</u>	<u>39.2</u>
	2.65	2.81	36.6 ^o

It seems that slopes more than about 36° are difficult to record.

From a navigational point of view it is very cumbersome to have the antenna on a sled behind the vehicle. This makes it impossible to reverse. If the antenna is mounted on cantilevers, hanging freely above the ground, the vehicle is free to move at its full capacity. This arrangement was tested for 120 MHz and 80 MHz antennas which both work very well when lying on a sled. The result was that this arrangement is possible for the 80 MHz antenna but not for the 120 MHz antenna, Figure 2.17 - 2.19.

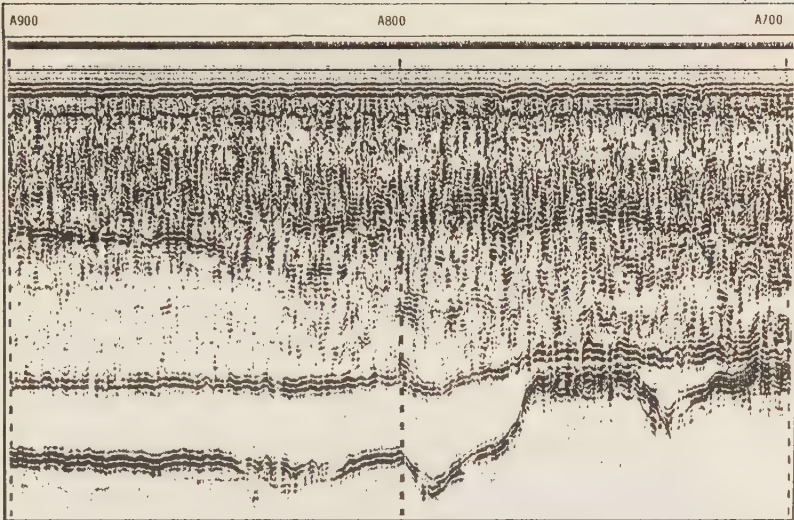


Figure 2.17. Record with 80 MHz antenna on a sled.

|ULRIKSEN 1982|

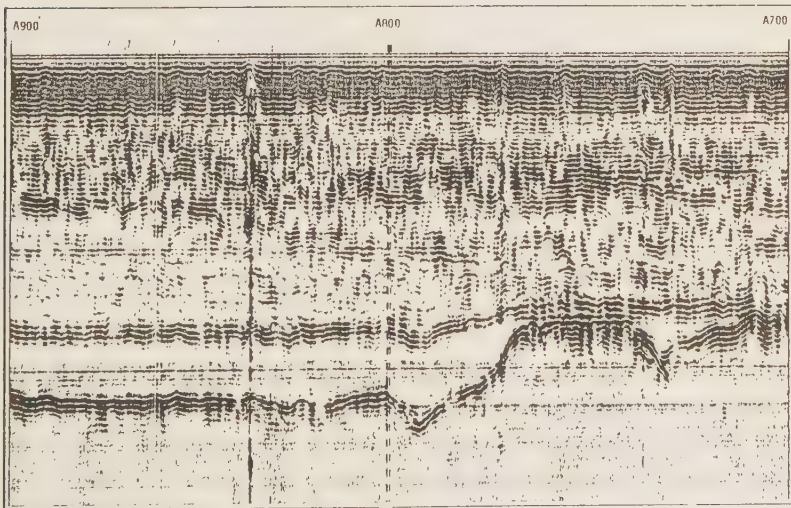


Figure 2.18. 80 MHz antenna mounted on cantilevers 0.7 m above the ground.

|ULRIKSEN 1982|

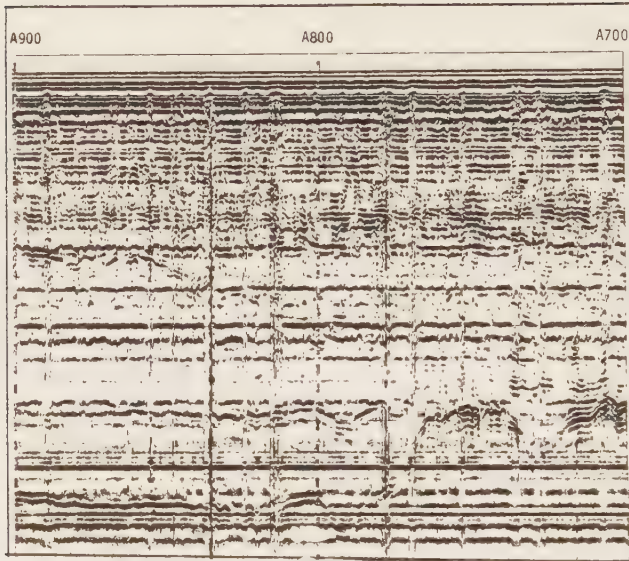


Figure 2.19. 120 MHz antenna mounted on cantilevers 0.7 m above the ground. [ULRIKSEN 1982]

Vehicle speed checks were performed with real time recording, i.e. directly on the graphic recorder. When the velocity reaches 20 km/h it was difficult to trace the radar return from the bottom. This is a very unpleasant speed to drive in. The tracked vehicle jumps between the humps on the surface of the peat bog and there is considerable mechanical stress on the equipment. Comfortable speed was 5 km/h maximum. Using the tape recorder it is feasible to profile at a velocity of 160 km/h. This is of course only hypothetical if an aircraft is not used.

An early test had shown that it was possible to obtain returns from the ground water table when the antenna was hanging at a height of about 2 m above a free, smooth surface on a drained peat bog, Figure 2.20.

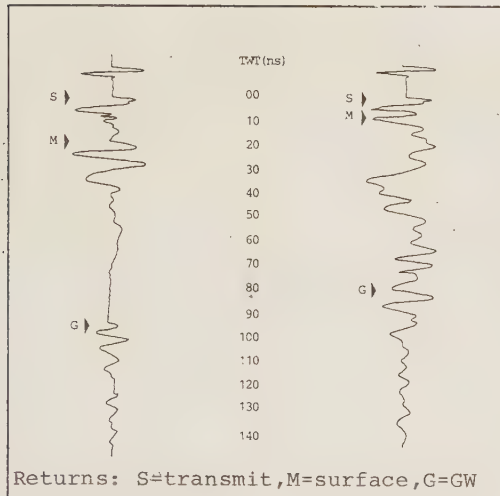


Figure 2.20. Radar returns with an antenna on the ground and with an elevated antenna. [BJELM and ULRIKSEN 1980.]

In this experiment the peat surface was dry. In a natural peat bog the surface will be rough and wet and thus produce a stronger reflection, less transmission, a lot of clutter and increased refractive gain.

Next the antenna was mounted beneath the fuselage of the helicopter as in Figure 2.21.

The flight was perpendicular to the production fields. In the profile plane a section of the peat bog is presented in Figure 2.22a. Figure 2.22b shows the resulting profile. No interpretable echoes were obtained.

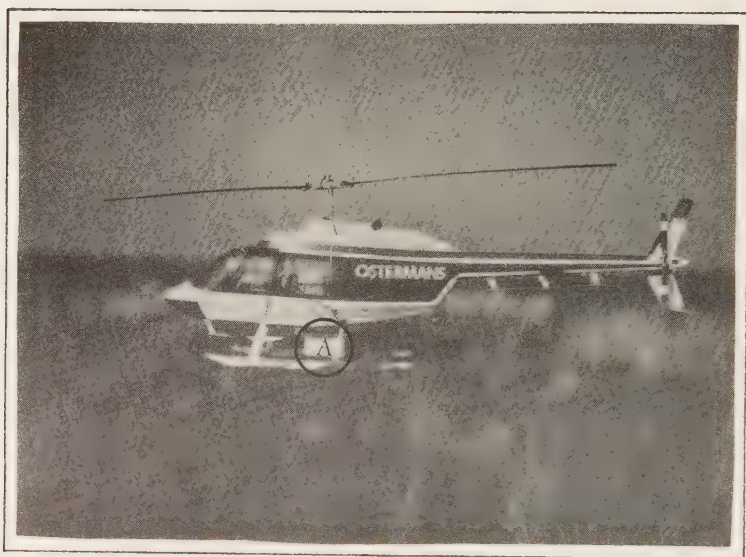


Figure 2.21. Bell Jet Ranger with 120 MHz antenna (A) mounted beneath the fuselage. [BJELM and ULRIKSEN 1980.]

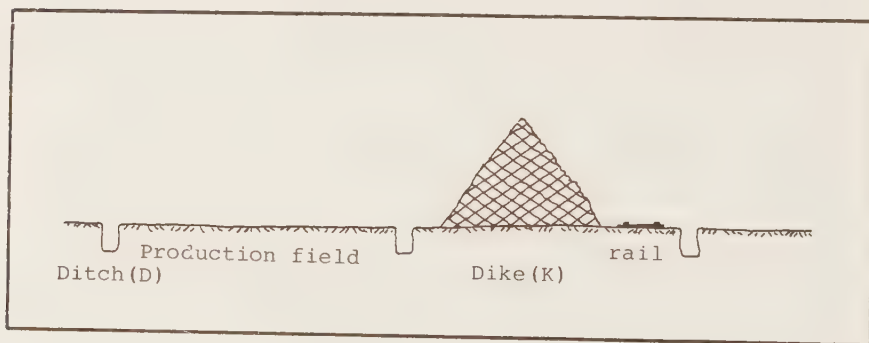


Figure 2.22a. Section in the profiling plane. [BJELM and ULRIKSEN 1980.]

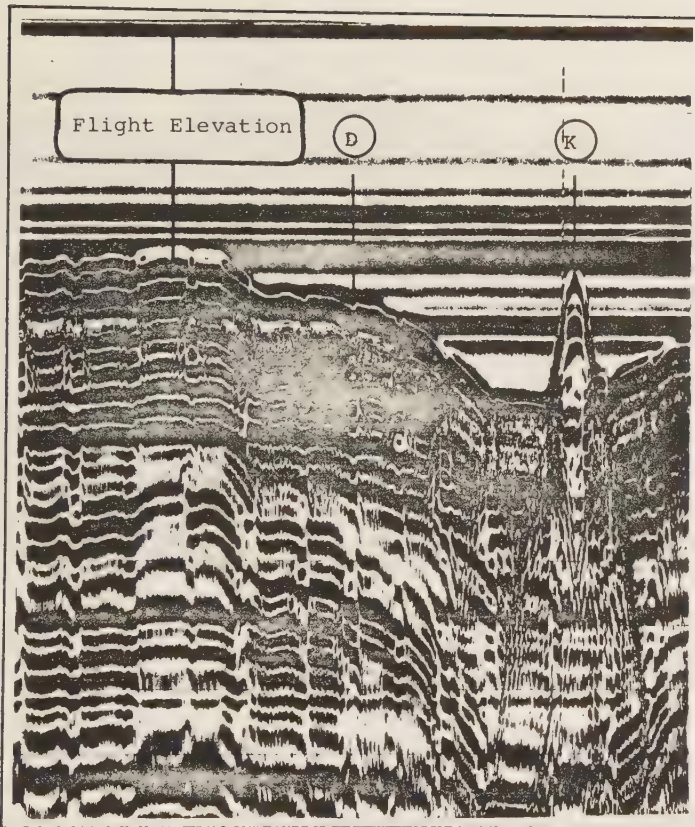


Figure 2.22b. Radar profile registered with the 120 MHz antenna mounted beneath the cabin of a Bell Jet Ranger helicopter. [BJELM and ULRIKSEN 1980.]

The next experiment, ULRIKSEN 1982, was conducted with the 80 MHz antenna hanging 5 m below the helicopter cabin, Figure 2.23. This arrangement gave less returns from the helicopter and allowed the antenna to be flown closer to the surface of the peat. This was essential since it is believed that the surface scatterers produce echoes with such a delay that they interfere with desirable returns from the bottom of the peat bog. If the flight height is decreased so is the area which can produce surface clutter. This means that the surface clutter will be limited in time and that it will not interfere with bottom echoes.

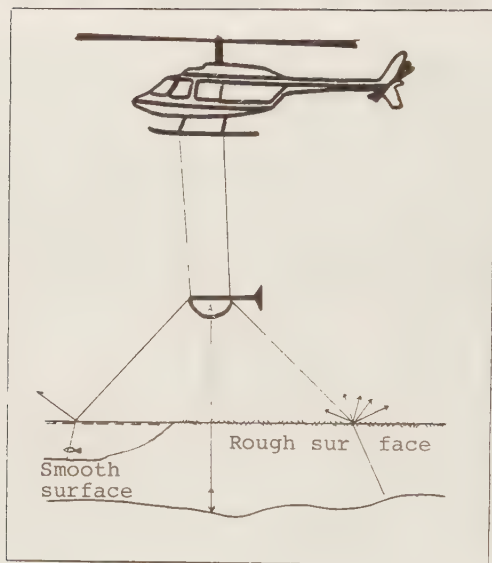


Figure 2.23. 80 MHz antenna hanging from helicopter.

[ULRIKSEN 1982.]

The previously mentioned radiation angle of 36° is only valid when the antenna lies on the ground, it is larger when the antenna is freely suspended in the air.

Also, as indicated in the figure, one may expect a better record over a smooth specular surface like that of calm water than over peat. In addition to this the refraction gain over water is stronger than over peat.

A radar profile recorded over the peat bog is presented in Figure 2.24. On the right side of the record, the helicopter rose to an elevation of 25 meters.

It is clearly possible to distinguish an independent return (R1) in parts of the record. The quality is not nearly as good as when the antenna lies directly on the surface or hangs from cantilevers 0.7 m above the surface.

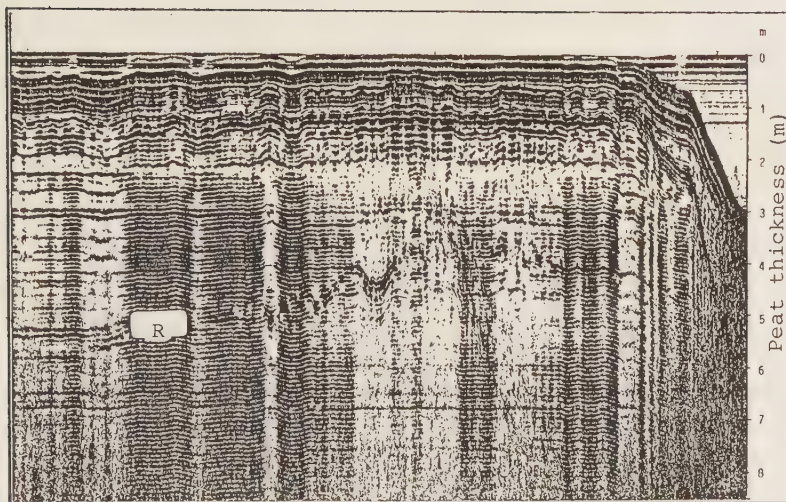


Figure 2.24. Radar record with the 80 MHz antenna hanging below the helicopter about 2 m above the peat surface.

[ULRIKSEN 1982.]

The helicopter was flown over the small pond in the south-eastern part of the peat bog. The record produced during this flight is presented in Figure 2.25. It is interesting to note that the pond is about 7 m deep, which is almost the same depth as the thickness of surrounding peat. The difference is attributed to the lower surface of the pond (~ 0.5 m). The radar data may give the following hydrological model.

The hydrological situation is that the maximum elevation of the peat bog is +174 m which it is 200 m to the west of the pond. In the northwest a small creek flows at +169 m. 2 km eastwards there is a large lake at +181 m. Between the peat bog and the lake there is a hill with a maximum elevation of +215 m. It may be that there is a hydrological contact between the lake and the pond and that somehow the outflow from the previous lake, (now the pond) was prevented which could be due to the growing peat bog. Once this outflow was

stopped the water rose and the lake/peat bog could move up over the previous water-front, now the threshold across Figure 2.14. The hydrological contact may be a system of cracks in the bedrock under the hill.

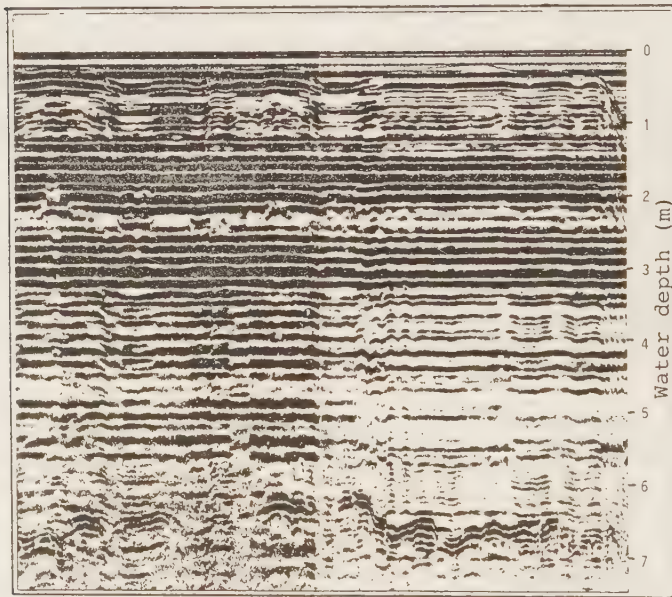


Figure 2.25. Radar record with the 80 MHz antenna hanging from a helicopter above the pond at Dala Mosse. |ULRIKSEN 1982.|

Profiling in Rock

Most rocks, except for the ores and shale, have electric properties that make them transparent to electromagnetic waves. On the other hand, the ores and shale are good targets due to their strong reflectivity.

From an engineering point of view the most interesting features in rocks are cavities and fractures. Radar has proved to be capable of detecting both.

At Ignaberga in Skåne large caves are accessible from the surface. Radar profiles were recorded on the surface, above those caves, SKANRAD AB 1981. The result is presented in Figure 2.26.

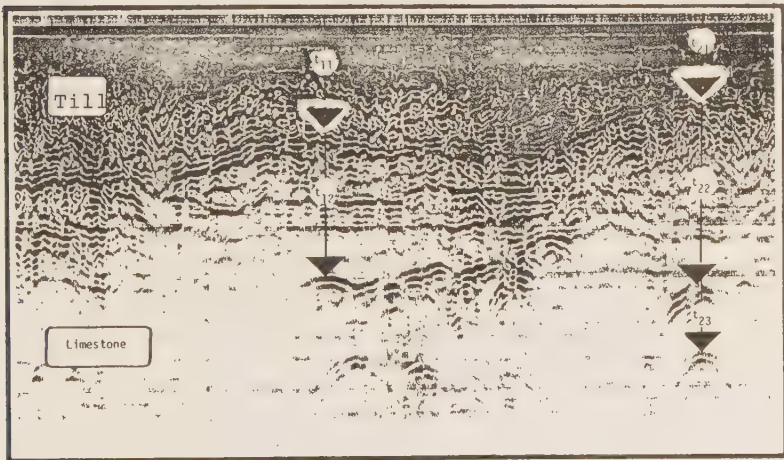


Figure 2.26. Radar profiles recorded at Ignaberga showing cavities in limestone. |SKANRAD AB 1981.|

This record is especially interesting since the limestone lies under a layer of till. Since no drillings were performed and no other means of determining the velocities were available the depths had to be calculated by assumed values of radiowave velocity. If we assume a relative permittivity of 9 in the dry moraine and 4 in the equally dry limestone the left cave has its roof 10.7 m below the surface and the right cave has its roof 12.4 m below the surface. For the right cave there were two echoes which were interpreted as coming from the roof and floor of the cavity. The calculated height of the cave is 7.4 m.

Another cavity was studied south of Visby on Gotland, FOLLIN, SVENSSON and ULRIKSEN 1982. There was no soil cover and the antenna was dragged directly on the limestone surface. Since the cavity was accessible from a hole, the strike and dip could be observed and the profiles arranged in an optimum manner. The situation is presented in Figure 2.27.

At every meter in the profiles, a radar return signal was digitized and stored on magnetic tape. This was subsequently used for studying the sign of the reflection coefficients.

The anticipated ray-path geometry is presented in Figure 2.28. Since the cavity is formed like a sloping tube the reflections come from points to the left of the profile line according to Fermat's principle.

The five radar records are presented in Figure 2.29. The radar records contain two assumed point-source reflections I, II and three horizontal reflections, A, B, C that are interpreted as layer-interfaces. The points where the digitized returns proved to be of most value are marked with a D.

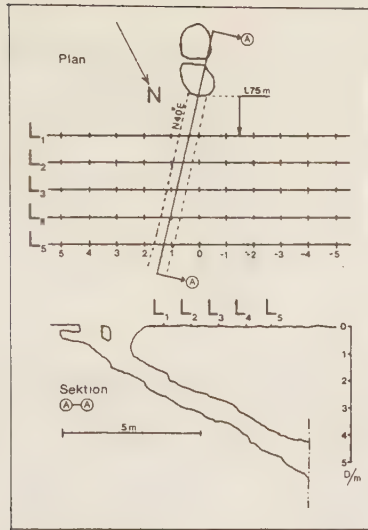


Figure 2.27. Experimental arrangement at Stenkumla south of Visby. [FOLLIN, SVENSSON and ULRIKSEN 1982.]

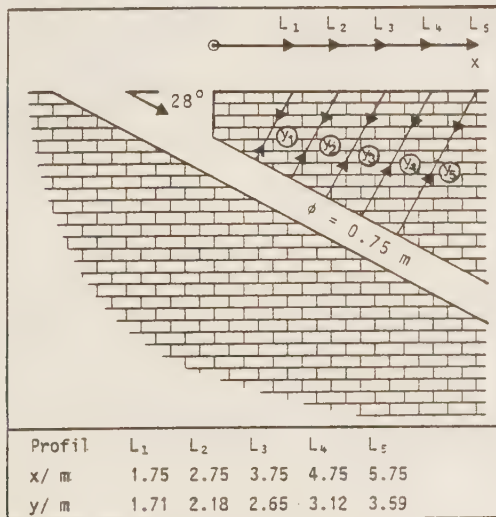


Figure 2.28. Anticipated ray-path geometry. [FOLLIN, SVENSSON and ULRIKSEN 1982.]

Assuming that the upper hyperbolic reflection in Figure 2.29 represents the roof of the cavity, the velocities can be calculated according to Table 2.6.

Table 2.6. Velocity calculation.

Depth (m)	twt (ns)	$\bar{v}$ (m/s $\cdot 10^8$)	$\bar{\epsilon}_r$
1.71	30.2	1.13	7.0
2.18	47.7	0.91	10.8
2.65	50.4	1.05	8.2 $\bar{\epsilon}_r = 8.5$
3.12	55.9	1.11	7.3
3.59	72.4	0.99	9.2

Another way would be to use the point-source method, which only requires a horizontal distance scale and a vertical time scale. This requires rather complete hyperbolas so it is only performed for lines 1 and 3, using (1.66). The result is presented in Table 2.7.

Table 2.7. Point-source calculations for the cavity roof (I).

Profile	x (m)	twt (ns)	z (m)	$\bar{z}$ (m)	$\bar{v}$ (m/s $\cdot 10^8$)	$\bar{\epsilon}_r$
1	0	36	-			
	1	41	1.83			
	2	55	1.73	1.77	0.98	9.4
	3	71	1.76			
3	0	51	-			
	1.4	57	2.80			
	2.4	68	2.72	2.64	1.04	8.3
	3.4	88	2.41			

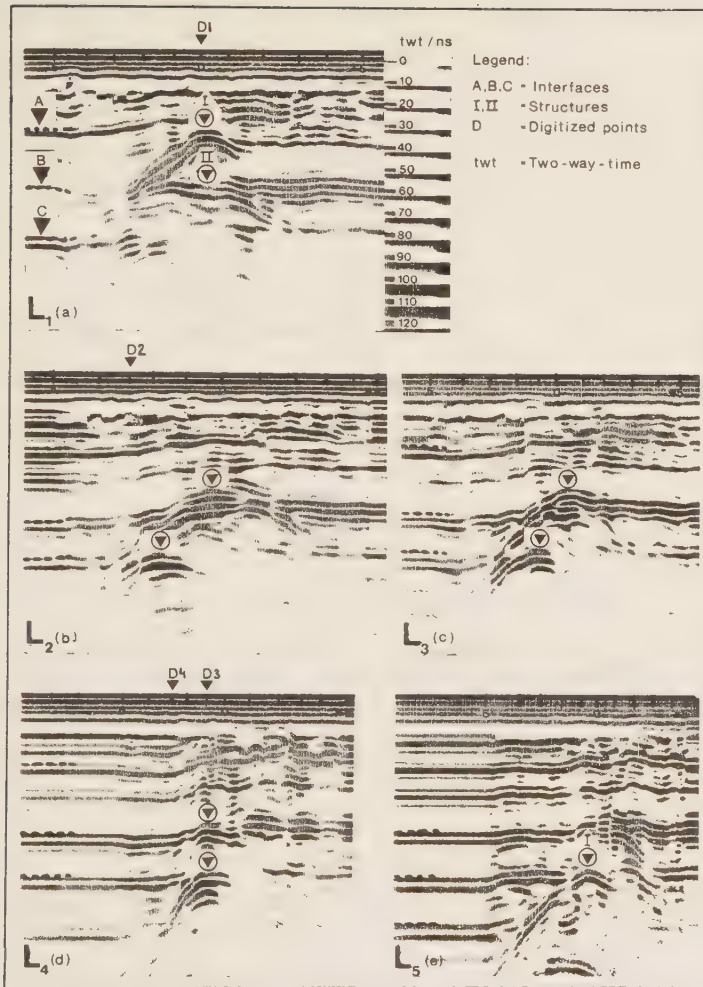


Figure 2.29. Radar records from the five profile lines.

[FOLLIN, SVENSSON and ULRIKSEN 1982.]

The same operation is performed for the lower point-source reflection (II) now in profiles 1, 4 and 5. The result is listed in Table 2.8.

Table 2.8. Point-source calculation for reflection II.

Profile	x (m)	twt (ns)	z (m)	$\bar{v}$ (m/s $\cdot 10^8$)	$\bar{\epsilon}_r$ (-)
1	0	57	-		
	1.6	64	3.13		
	2.6	71	3.51	3.43	1.20
	3.6	80	3.66		6.3
4	0	80	-		
	1.3	88	2.83		
	2.3	96	3.46	3.20	0.80
	3.3	113	3.30		14.1
5	0	79	-		
	1.6	88	3.26		
	2.6	95	3.89	3.71	0.93
	3.6	107	3.94		10.4
	4.6	125	3.75		

The result indicates that the reflection (II) in profile 1 may be of a different character than (II) in the other profiles. It cannot be a branch of a tree because then the velocity would have been $\sim 3.0 \cdot 10^8$ m/s.

The velocities calculated for (I) are somewhat higher than those calculated for (II). This is natural, since (II) lies deeper and may be surrounded by more humid limestone.

In order to strengthen the interpretation the digital radar return records are evaluated. First a theoretical model according to Figure 2.30 is studied. It is built to match the situation in profile 1, 0. The impedances are calculated for 300 MHz, the center frequency of the antenna used for the digital recordings.

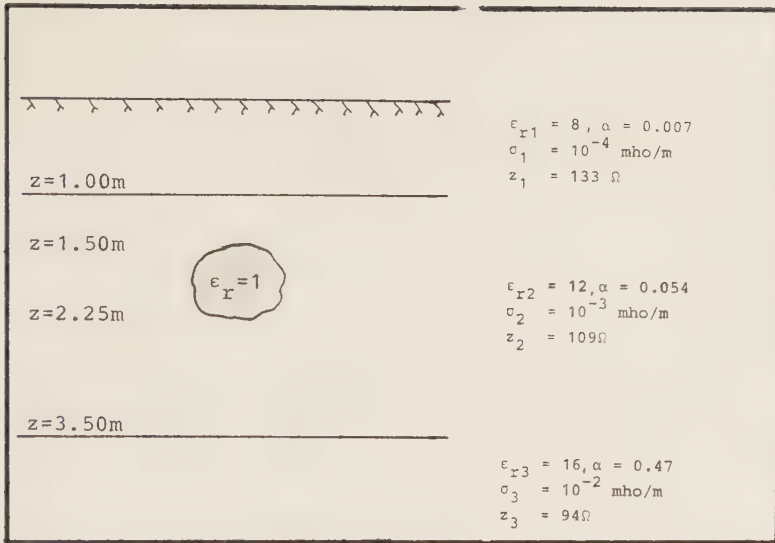


Figure 2.30. Theoretical model of the cavity.

Using the permittivities, impedances and attenuations presented in Figure 2.30 makes it possible to calculate the expected shape of the radar returns. This is done by convolution of the transmitted impulse with the series of properly delayed reflection coefficients in which the attenuation is also included.

Assuming that the impulse has a unit positive amplitude at the surface of the bedrock, the following sequence of reflection coefficients can be calculated using the data from Figure 2.30.

Table 2.9. Sequence of reflection coefficients with attenuation included.

Object	Depth (m)	Delay (ns)	Attenuation factor, A	Reflection coefficient, r	Value A·r·T
First interface	1.00	18.9	0.96	-0.099	-0.095
Cavity roof	1.50	30.4	0.90	+0.55	+0.45
Cavity floor	2.25	32.4	1.00	-0.55	-0.25
Second interface	3.50	65.4	0.76	-0.074	-0.011

T is the amplitude of the transmitted impulse after the previous reflection.

The 300 MHz antenna has a wavelength of 1 m in air and consequently the first destructive interference distances are 0.25 and 0.75 m. The latter will be much weaker than the first and although 0.75 m is the model cavity height it will be ignored in these calculations.

The unit impulse used for the convolution process is presented in Figure 2.31.

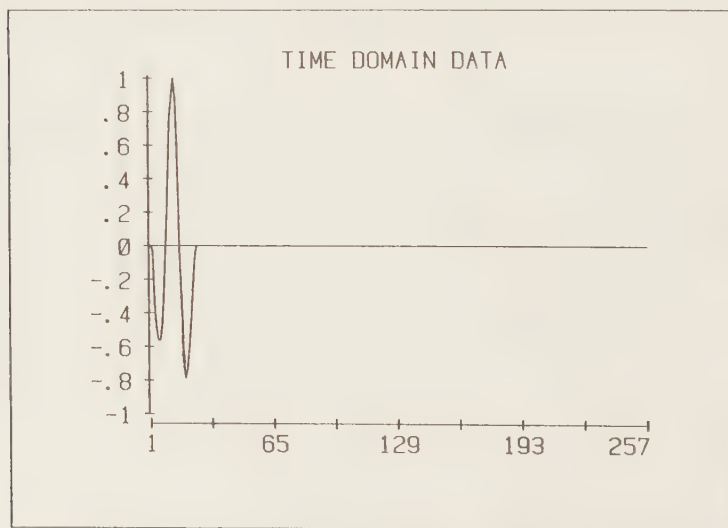


Figure 2.31. Unit impulse used for the convolution process.

The sequence of attenuation-correlated reflection coefficients is presented in Figure 2.32 and the result of the convolution process is presented in Figure 2.33.

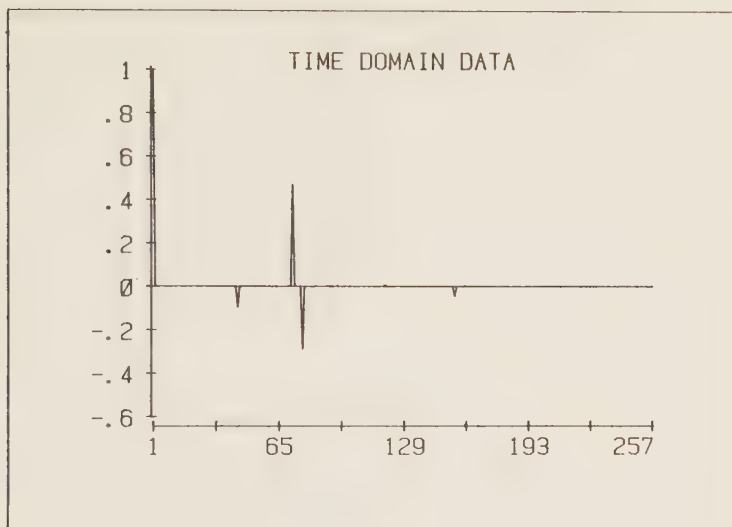


Figure 2.32. Sequence of reflection coefficients with attenuation included.

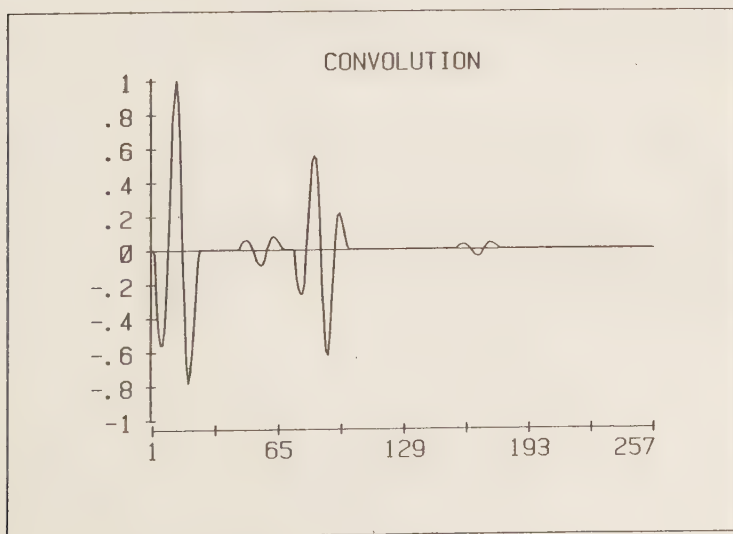


Figure 2.33. Convolution of the impulse with the sequence above.

The convolution produces what is called a synthetic radar signal in analogy with synthetic seismograms used in reflection seismics. It shows that there is no way the return from the cavity roof can be separated from the return from the cavity floor. These two returns interfere and the result is that there are four half periods in the cavity return while there are only three half periods in the model impulse. Consequently reflection (II) is not created by the cavity floor.

Now we shall consider the digitally recorded waveforms. These have passed through the antenna and through the amplifiers in the control unit. Compared to the synthetic radar signal there is a 180° phase change after the transmitted waveform which comes first in the signal. This is due to the fact that the transmitted signal is actually what is leaked into the receiver from the transmitter. The amplitudes may vary since there is an amplifier working exponentially with time. Thus late echoes may be stronger than what is predicted by the synthetic radar signal which is linear.

The digital record made directly over the cavity D1 is presented in Figure 2.34. It differs from the synthetic radar-gram only in that the return from the first interface A seems to be stronger. Otherwise the sign of the first half period is equal to the synthetic signal.

A better location for studying A would be in profile 2, at D2. This record shows more clearly that the reflection named A is caused by an increase in relative permittivity. There are two more echoes in this record but they are associated with a part of profile 2 where B interferes with I and C interferes with II. Thus they are not easily interpreted.

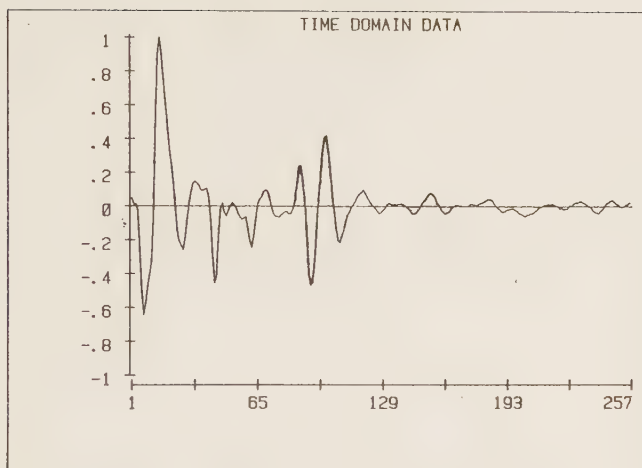


Figure 2.34. Digitally recorded signal in the center of profile 1, D1.

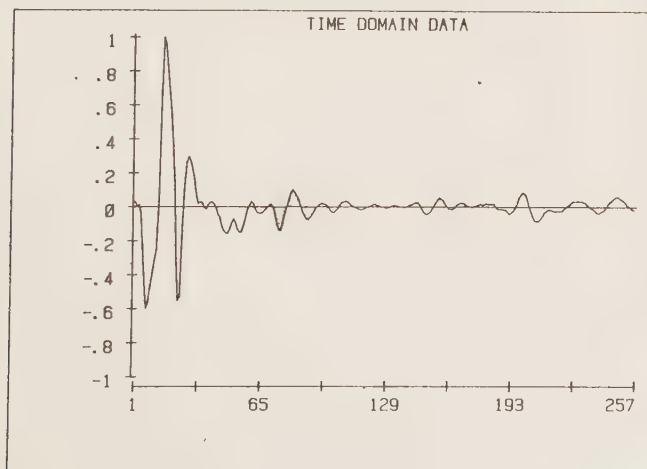


Figure 2.35. Digitally recorded signal to the left of profile 2, D2.

The third recorded signal is in profile 4 at D3, 1 m off the center, see Figure 2.36. It gives an impression of the characteristics of reflection II. It contains a reflection from I but it interferes with B so it may be difficult to interpret. II is seen to be of the same type as I in Figure 2.34, i.e. it may be a cavity. Another cavity at this depth would most likely interfere with the one there was access to. Consequently the interpretation is that due to the roughness of the cavity it may produce reflections from more than one point as indicated by Figure 2.28. For example it could be that the conditions were favourable for both reflections from the section anticipated to be valid for line 4 and for line 5. This would produce two separated reflections.

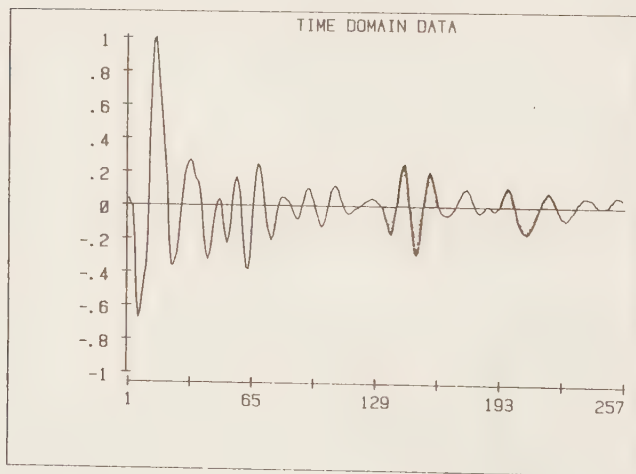


Figure 2.36. Digitally recorded signal in profile 4, D3.

The last signal that will be presented is recorded 3 m from the center of line 4 and gives good registrations of reflectors B and C, Figure 2.37. It shows clearly that they both are produced by an increase in impedance.

By using the digitally recorded waveforms it has been possible to show that all the horizontal reflectors are caused by increases in impedance and that II probably is not a multiple but a second reflection from the cavity.

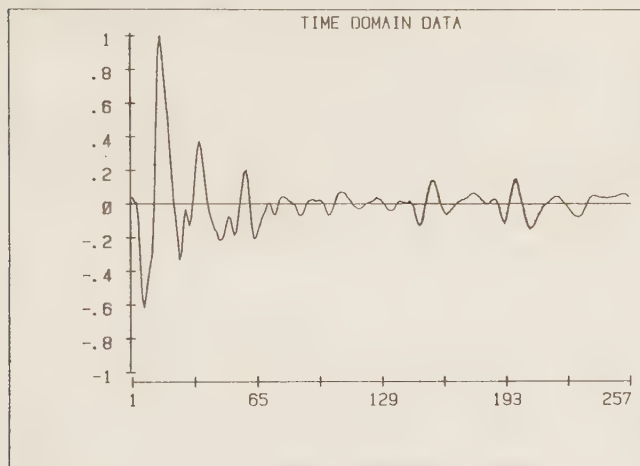


Figure 2.37. Digitally recorded signal in profile 4, D4.

Digital recording of waveforms in combination with a continuous radar record was subsequently used at another location east of Visby on Gotland, FOLLIN, SVENSSON and ULRIKSEN 1982. The continuous record is presented in Figure 2.38 and shows three layers dipping to the right of the profile. Between the distance marks 20 and 25 m there is a point-source type of reflection that possibly could be a cavity. There is only a very thin layer of soil so all recorded structures must be in the limestone. Three locations were chosen that gave strong returns from the three horizontal reflectors. Reflector 1 was recorded at distance mark 10 m, reflector 2 at distance mark 15 m and reflector 3 at distance mark 20 m.

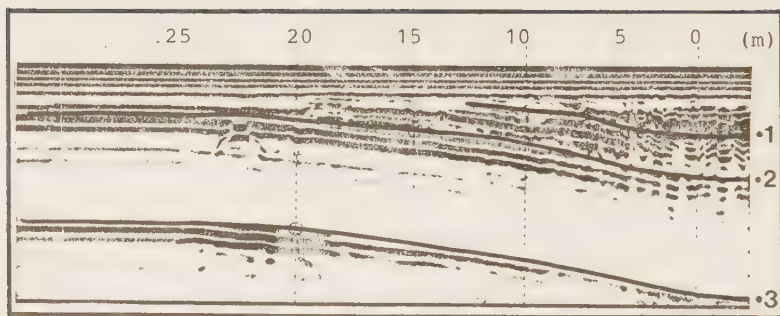


Figure 2.38. Continuous radar record east of Visby.

The signs of the reflection coefficients are studied and show that reflector 1 is caused by an increase of relative permittivity, reflector 2 is caused by a decrease and reflector 3 by an increase of relative permittivity. The layer between reflector 2 and reflector 3 consequently has a lower relative permittivity than the surrounding layers, $\epsilon_1 < \epsilon_2$, $\epsilon_2 > \epsilon_3$ and $\epsilon_3 < \epsilon_4$.

If there was no attenuation the reflection coefficients could be calculated and the velocity changes obtained. If one velocity could be determined the other ones could too. Unfortunately there is attenuation which is not easily calculated from the radar signals. Theoretically the dispersion of different frequency bands could perhaps give such information.

The lower permittivity of the third layer has two possible explanations. Either the surrounding layers are saturated and the permittivity is lower due to a lower porosity of

layer 3 or the layers are dry and the permittivity of layer 3 is lower due to a higher porosity.

In a nearby quarry two water tables are situated at +55.0 and +54.2 m. At distance mark 10 m the elevation of the ground surface is 53.67 m, which is below the observed water tables.

Since no extended point-source reflections are available the radiowave velocity in the limestone is assumed to have the same average value as those previously encountered. By using this velocity the depths to the three layer interfaces are calculated at distance mark 10. The depths are about 0.8, 1.6 and 3.9 m.

This information makes it probable that the ground water table may be situated at the level of reflector 1. If this is the case, the first explanation of the low permittivity of the third layer is valid, i.e. the low permittivity is caused by a lower porosity as compared to surrounding rocks.

Detection of fractures is the second capacity of radar use that has been studied, BJELM, FOLLIN and SVENSSON 1982. At Finnsjön in Uppland a dipping structure assumed to be a fracture was recorded.

The notation Ø4 indicates the position of a core-drilled hole, dipping 80° and striking N50E. Several fracture zones are observed. The rock is a granodiorite for which the tabular value of the radiowave velocity is given to be $1.03 \cdot 10^8$ m/s at a frequency of 10 MHz. However there is a weak point-source reflection at the center of the record, which may give a velocity determination. The velocity determined in this way is $0.83 \cdot 10^8$ m/s and by using (1.71) to correct the dip-angle in the record, the intersection of the drill-hole and fracture zone is calculated to be 9.9 m. There are two pronounced fracture zones around 10 m, which makes it probable that the point-source method yields a good estimate of the velocity, ULRIKSEN 1981.

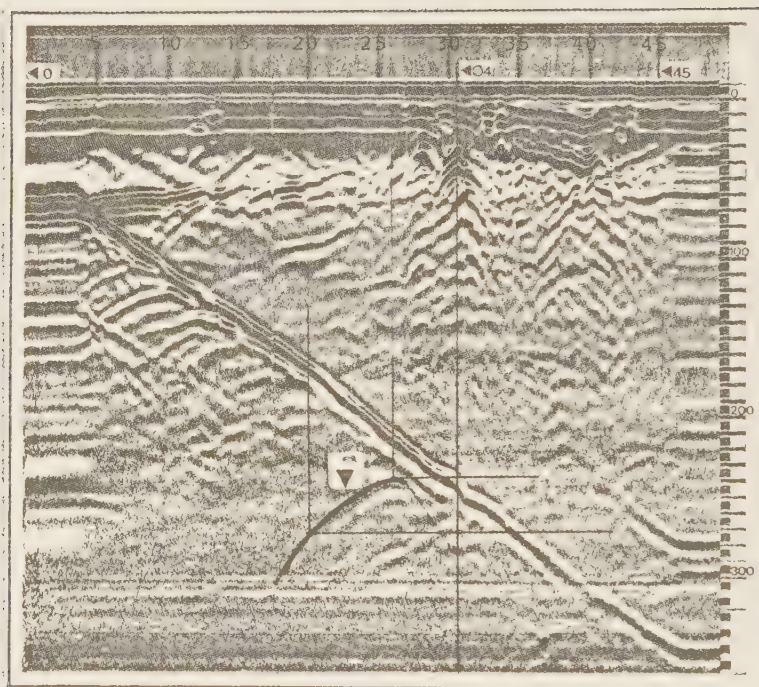


Figure 2.39. Record of a dipping fracture at Finnsjön in Uppland. [BJELM, FOLLIN and SVENSSON 1982.]

Another example is the detection of a horizontal banking-plane. Near Ronneby in Blekinge where E66 cuts through rock a banking plane is visible about 4 m below the free surface of the rock. The situation together with measured distances at the free rock side, D and delay times, t_{wt} is presented in Figure 2.40, BJELM, SVENSSON and FOLLIN 1982. These measurements gave an average velocity of $1.37 \cdot 10^8$ m/s with very little variance.

Since the reflector is flat the CDP-method could also be used. The calculations are presented in Table 2.10 and give a reflector depth of 4.32 m and an average velocity of $1.37 \cdot 10^8$ m/s with even less variance. These calculations

were performed with algorithms presented by ULRIKSEN 1981 which use linear regression for the important determination of the zero-time location in the continuous radar records. Otherwise (1.64) is used as usual.

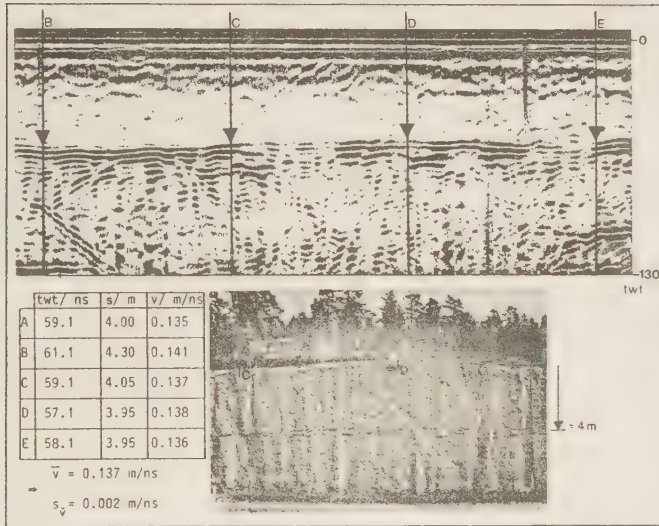


Figure 2.40. Detecting a horizontal banking-plane with radar. [BJELM, FOLLIN and SVENSSON 1982.]

These examples show that there are wide possibilities to obtain information about features in rock without costly drillings. In short the tools are digital recordings of wave-forms, the CDP-method and the point-source method. The latter two methods are especially suited for measurements in rock, since these have low attenuation and are homogenous in comparison to many soils. This will make wide antenna separations possible and give long hyperbolic point-source tails, both allowing many calculations of depth and velocity to yield a good average depth-value.

Table 2.10. CDP-calculations of depth and velocities at Ronneby. [BJELM, FOLLIN and SVENSSON 1982.]

pkt	x_i / m	s / m	v / m/ns
1	0.31	4.10	0.137
2	0.41	4.22	0.137
3	0.51	4.36	0.137
4	0.61	4.37	0.137
5	0.71	4.49	0.137
6	0.81	4.46	0.137
7	0.91	4.40	0.137
8	1.01	4.49	0.137
9	1.11	4.35	0.137
10	1.21	4.37	0.137
11	1.31	4.35	0.137
12	1.41	4.25	0.137
13	1.51	4.01	0.137
14	1.61	-	0.137

CDP :

$\bar{s} = 4.32 \text{ m}$

$\bar{v} = 0.137 \text{ m/ns}$

$s_{\bar{v}} = 0.0001 \text{ m/ns}$

Location of Pipes and Cables

When crossed at right angles pipes and cables can be considered point-targets. A very good example of radar-profiling is presented in Figure 2.41 which shows drainage pipes and the associated ground water table in a drained peat bog. This is actually a "photograph" of a dynamic hydraulic process, ULRIKSEN 1980.

In Figure 2.42 is an enlargement of the profile around a pipe reflection. The two returns come from the upper and lower parts of the Ø300 mm concrete drainage-pipe, which is waterfilled.

The point-source method is applicable for determining the depth to the source and the average velocity.

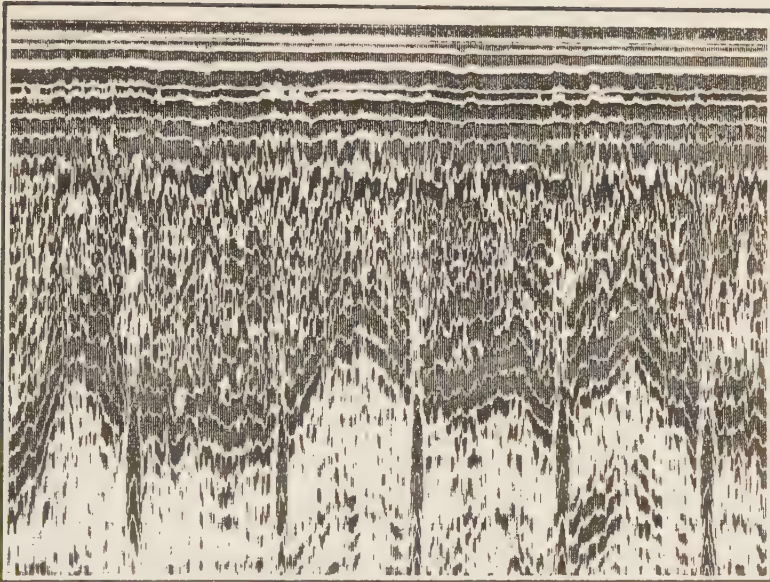


Figure 2.41. Radar profile showing drainage pipes and the associated ground water table. [ULRIKSEN 1980.]

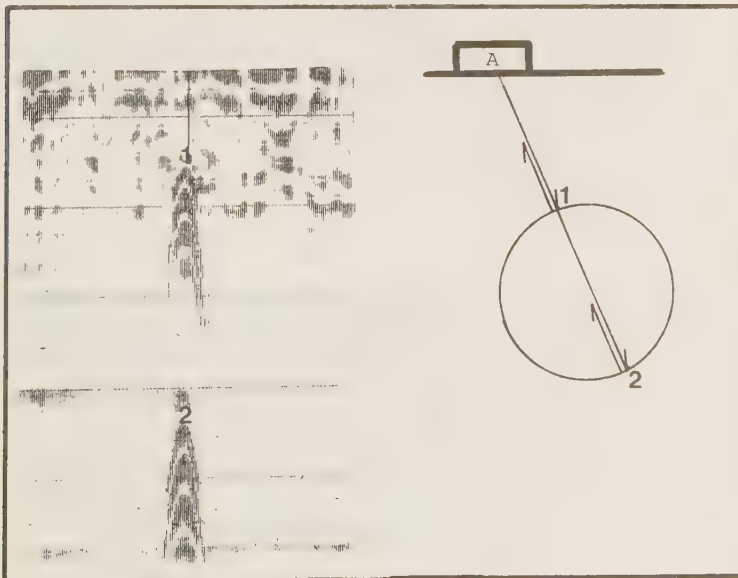


Figure 2.42. Radar returns from the upper and the lower part of a concrete drainage-pipe.

Consider a pipe lying in sand, which has a leakage. If there is some capillarity in the sand the water will invade the zone above the pipe and produce a higher permittivity for the invaded layer.

If there is an oil-leakage from an electric high-power cable and the cable is buried below the ground water table, the oil will replace the water in the pores above the cable, thus producing a lower permittivity of the invaded zone.

These two cases will change the delay time to the vertex of the hyperbola and also the angle produced by the two tails of the hyperbola. In Figure 2.43 is a presentation of how the shape of a point-source hyperbola changes with the velocity for the hypothetical case where there are no attenuation changes and no change in the radiation pattern when the velocity changes. Both effects will tend to make the width of the hyperbola smaller. Decreasing velocity is seen to make the angle between the tails smaller and the delay time to the vertex longer. Comparison from one radar record to another is easier to do with the tail angle. Nor is the tail angle dependant on actual depth.

If traverses are made across a leaking pipe or cable the tail angle will be smaller over the water leakage while it will be larger over the oil leakage. This has been confirmed for water leaks by "examensarbete" by PETERSSON 1982 under the guidance of the author and for leaking high-power cables by ULRIKSEN 1981.

PETERSSON also studied if it was possible to detect the water level in a non-conducting pipe, e.g. plastic or concrete. In order to get short wave-lengths, the 900 MHz antenna was used and the Ø300 mm plastic pipe immersed in a water tank. Records were made with the pipe empty, 1/4-, 1/2-, 3/4- and 1/1-full. The results are presented in Figure 2.44 a-e. Stronger bottom and full-pipe echoes are expected in soil due to the lower relative permittivity.

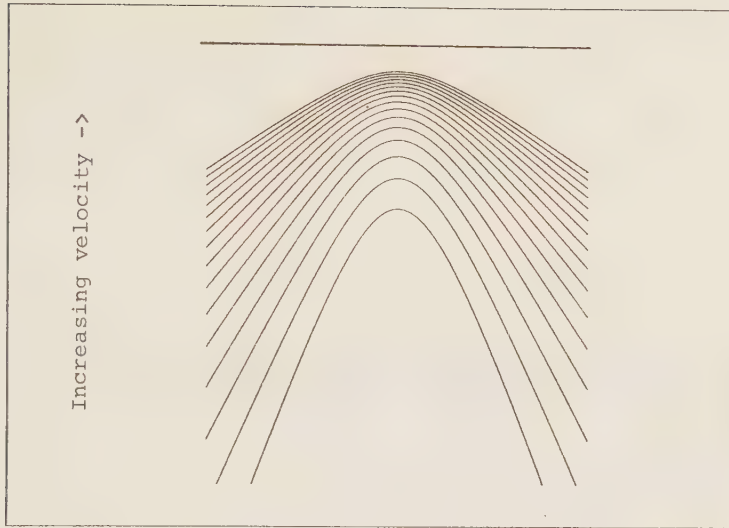


Figure 2.43. Point-source hyperbolas for varying velocities.

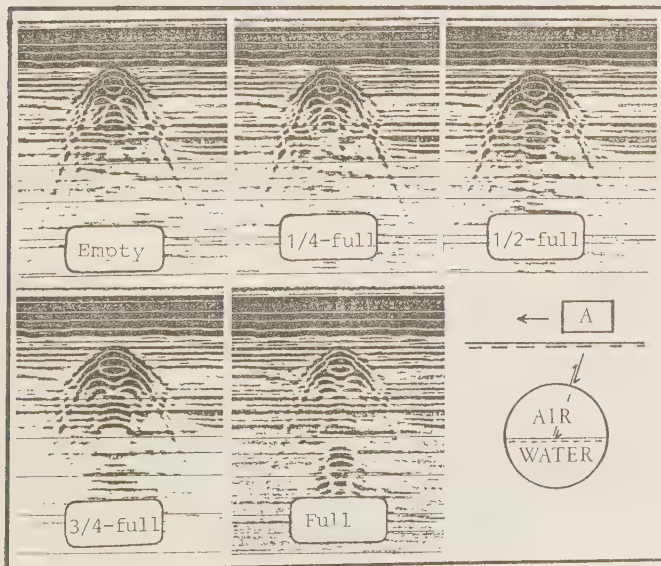


Figure 2.44. Records of a $\varnothing 300$ mm plastic pipe with different levels of water inside. |PETERSSON 1982.|

Measurements in Freshwater

Due to the low conductivity and high permittivity of freshwater excellent radar records can be obtained. Penetration is about 10 m for an 80 MHz antenna and though the wavelength of this antenna is 3.75 m in air it is only 0.42 m in water which gives a good resolution.

The first results were presented by ANNAN and DAVIS 1977 who measured ice-thickness and underlying water depth. It may be difficult to do this at the same time, at least if the water has any substantial depth. The reason is that the low permittivity of ice makes the delay time very short compared to the long delay times which the water will produce. In order to get good resolution in ice a high-frequency antenna should be used while for water a low-frequency antenna is more adequate.

An example of radar profiling of water depth from the ice surface is presented in Figure 2.45. The record was made at Krankesjön in Skåne and contains a multiple reflection which is very rarely observed in radar records. Its appearance is due to electromagnetic energy being trapped between two highly reflective interfaces. The water depth is calculated using $\epsilon_r = 81$ and if the water depth is of some dignity the delay time in the ice may be neglected.

The antenna may also be put directly into the water and towed behind a boat or hanging from a bridge. An example where the antenna was towed behind a rowboat in a water-filled gravel pit is given in Figure 2.46. As in peat bogs, it is possible to separate different bottom types by studying the shape of the bottom return. If the return is strong and smooth, the bottom is composed of fine sediments. If it is speckled and weak, the bottom may be moraine. Boulders lying on the bottom beside the profiling line may produce hyperbolic reflections that lie under the bottom in the record appearing as sub-bottom rocks. These can be separated by the point-source method. Boulders lying on the bottom

give the radio-wave velocity in water, and boulders actually lying below the surface give a higher radio-wave velocity. This provides a theoretical possibility to determine how far from the sides of the profile-line a bottom-boulder lies. The difficulty lies in determining the position at the water surface. When measurements are performed from the ice surface this is no problem.

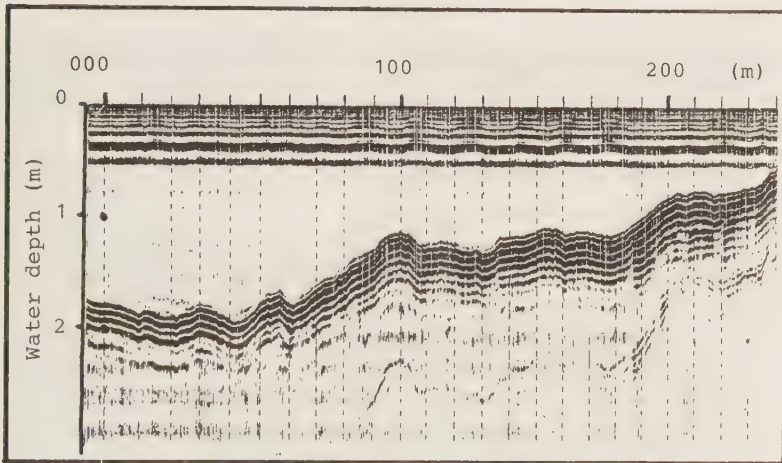


Figure 2.45. Radar profile of water depth recorded from the ice surface.

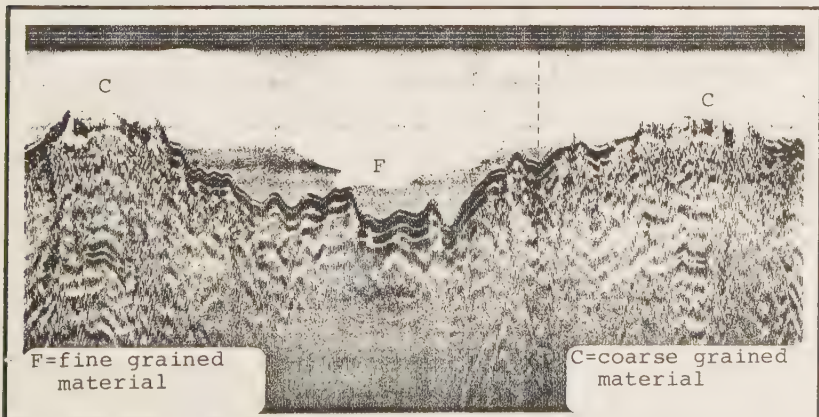


Figure 2.46. Record with 80 MHz antenna towed behind a boat in a waterfilled grave pit.

Due to the homogeneity of freshwater it may be possible to calculate reflection coefficients of a smooth bottom from the bottom surface return if digital records are made. Performing a linear regression of the power reflection coefficients $R(\text{twt})$ in dB versus the delay time, twt , gives a relation that explains the attenuation in the water and the average power reflection coefficient, R_a . If the value calculated from this relation is subtracted from the present power reflection coefficient, $R(x, \text{twt})$, at a certain location, x , the residual, $\Delta R(x)$, will give the deviation of the power reflection coefficient, in that point, from the average, R_a .

Assume the regression yields

$$R(\text{twt}) = a + b \cdot \text{twt}$$

then

$$\Delta R(x) = R(x, \text{twt}) - (a + b \cdot \text{twt})$$

and the true power reflection coefficient $R(x)$

$$R(x) = R_a + \Delta R(x)$$

There is no simple way to separate the average power reflection coefficient effect from the attenuation effect. The relative variations of bottom power reflection coefficients $\Delta R(x)$ are believed to be sufficient for separating different bottom soils.

FAGERGREN and STAHLÉ 1982 did their "examensarbete" under the guidance of the author and they studied if the depth of rapidly streaming water could be determined with radar. This was not possible with the antenna in the air but if it was lowered to the water surface the result was excellent. The profile presented in Figure 2.47 is recorded at a bridge across Mörrumsån in Blekinge. The antenna was hanging from a bridge.

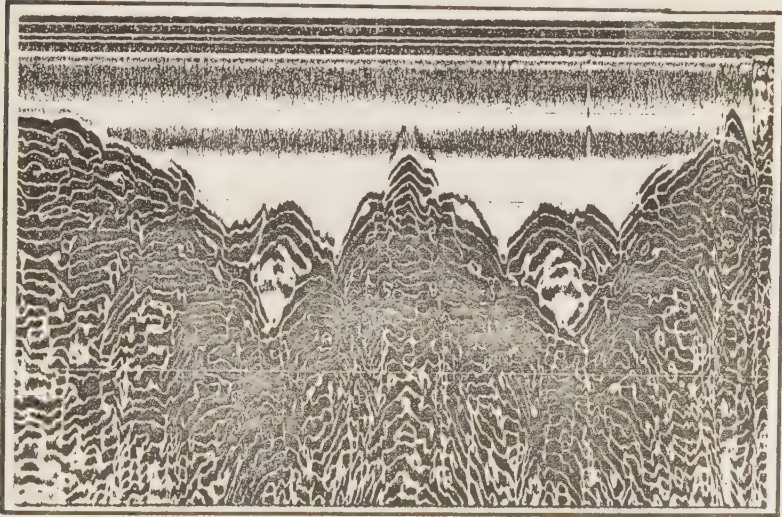


Figure 2.47. Radar profile across Mörrumsån. |FAGERGREN and STAHLÉ 1982.|

They also studied if it was possible to encapsulate the 900 MHz antenna in a water-tight container and to drag it along the bottom of a lake. This ought to give better bottom penetration but may be difficult to do for the bigger antennas.

Though it is a record of bad quality, Figure 2.48 shows how an interface below the bottom could be tracked continuously as the antenna was pulled up from the lake and along the dry surface of the beach. The water-front is in the center of the profile.

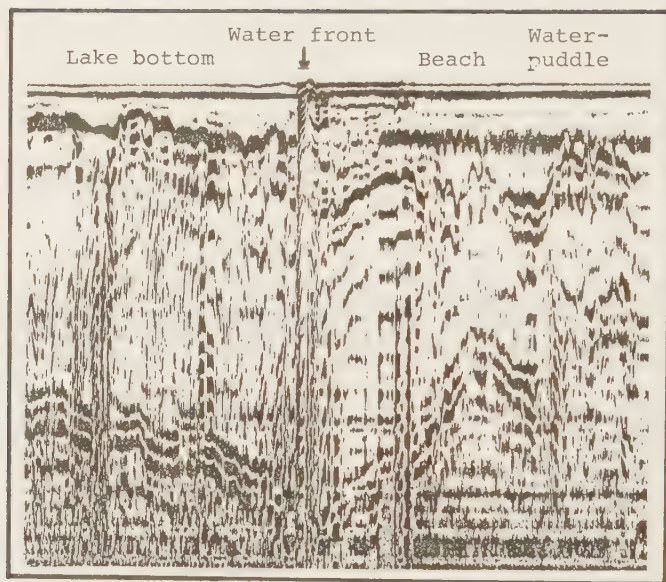


Figure 2.48. Radar record with 900 MHz antenna pulled at lake bottom up over the beach. [FAGERGREN and STAHL 1982.]

Resistivity surveys (Pat. pend)

The penetration of the radar impulses is highly dependant on the conductivity of the ground. This can be utilized to determine the conductivity variations of the soil along a profile under certain assumptions.

Suppose that the soil contains a number of scatterers and reflecting horizons of varying reflectivity. These may be described as a number of random reflection coefficients located at random delay times, $R(t)$, that when convolved (*) with the transmitted impulse, $I(t)$, build up the radar signal. Added to these is the conductivity-dependant attenuation $\alpha(z)$. Since $2z = v \cdot t$, the signal, $s(t)$, may then be described as

$$s(t) = R(t) * I(t) * e^{-\alpha\left(\frac{v \cdot t}{2}\right) \cdot v \cdot t} \quad (2.5)$$

where v = the radio-wave velocity.

Due to the large number of elements in $R(t)$ this parameter always has a rather constant absolute sum. $I(t)$ has a constant absolute sum. Integrating the absolute value of $s(t)$ would give the integral value I

$$I = \int |s(t)| dt = \int |R(t)| * |I(t)| \cdot e^{-\alpha(\frac{v \cdot t}{2}) \cdot v \cdot t} \quad (2.6)$$

which also may be expressed as

$$I = c_0 \int e^{-\alpha(\frac{v \cdot t}{2}) \cdot v \cdot t} dt \quad (2.7)$$

where c_0 is a proportionality factor.

The instrument necessary to perform $\int |s(t)| dt$ is called a partial trace integrator and is described in chapter 4.

I will be proportional to the attenuation of the impulse in the soil, which is calculated according to (1.2)

$$\alpha = \omega \sqrt{\frac{\mu \epsilon}{2} \left(\sqrt{1 + \left(\frac{\sigma}{\omega \epsilon} \right)^2} - 1 \right)} \quad (1.2)$$

where σ and ϵ are functions of the depth. Since σ is expected to vary several magnitudes while ϵ only varies a little more than one magnitude, the attenuation may be considered a function of the conductivity. Very wet soils, such as peat, may seriously affect the dependence of the attenuation on conductivity. A thin layer of high conductivity reflects most of the incident energy and absorbs the rest. Consequently no information would be available below such a layer. For resistivity surveys in relation to pipe burial this is not a serious problem, since the burial depth normally is small, e.g. 1 - 2 m.

The method gives an excellent possibility to detect zones where there are large conductivity changes. These zones are known to be the most serious areas when concerned with the corrosion of metallic pipes. Once the zones are detected it is a matter of only minutes to determine the absolute

conductivity change with conventional methods, e.g. a resistivity survey using the Wenner arrangement of electrodes.

A simpler method, which can be used to evaluate conductivity changes from normal radar records, would be to determine the delay time for the last interpretable echo that lies over the noise level. This was done in an early experiment in Revinge in Skåne, ULRIKSEN 1980, and followed up with conventional resistivity surveys performed by the resistivity group of Gustavsberg AB, a major manufacturer of iron pipes. The result is presented in Table 2.11.

Table 2.11. Last returns and measured resistivity. [ULRIKSEN 1980.]

Obs	Soil type	Last return (ns)	Resistivity (Ohmm)
1	Boulder clay	20	110
2	Boulder clay	50	230
3	Clayey moraine	10	60
4	Clayey moraine	10	30
5	Peat	50	30
6	Peat	45	30
7	Sand	130	4400

Note the late returns in peat compared to obs 4 which is of the same conductivity. The reason for this is the favourable circumstances of radar profiling in peat, namely that it is a homogenous soil of large relative permittivity. Taking the natural logarithm of the resistivity and plotting it against the last return times gives a linear relation, presented in Figure 2.49.

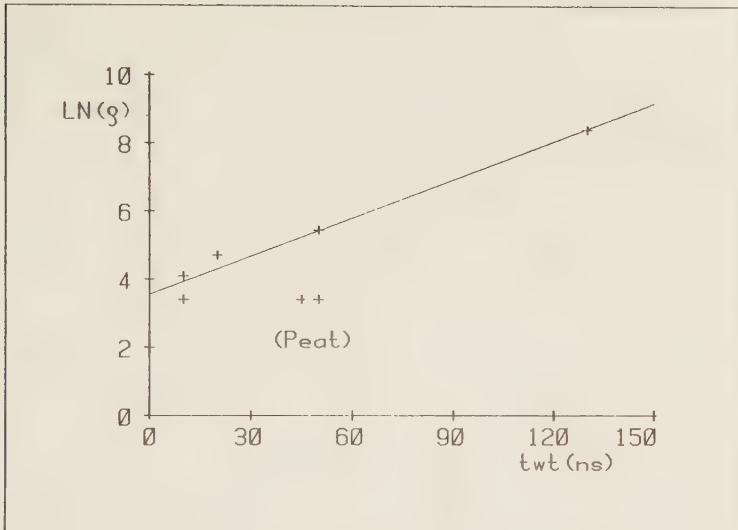


Figure 2.49. Relation between measured resistivity, (ρ), and last return time, (twt), in different soils along a profile. |ULRIKSEN 1980.

It serves no purpose to present the relation as a mathematical formula, since the absolute values are dependant on how the radar equipment amplifiers were tuned at that specific occasion. It is recommended that the exponential amplifier not be used, since it may affect the possibility to separate last returns from system noise.

3 MEASUREMENTS IN SNOW

The most challenging problem associated with measurements in snow is the determination of equivalent water content in the snow cover. This is the parameter of interest for hydrologists who want to predict spring run-offs. These predictions are essential in the regulation of reservoirs for hydroelectric power plants.

Other problems may be the location of people buried by avalanches and survey of snow thickness in alpine ski-resorts. This could be done with less sophisticated radar equipment than the present impulse radar system. The graphic recorder would be substituted by a small TV-monitor and the weight needs not be more than 5 - 10 kg.

Snow is a mixture of ice, air and in some cases water. Successful measurements of glacier thicknesses of several kilometres have been performed since around 1960, e.g. see articles in Journal of Glaciology. The success depends on the constant relative permittivity of ice, $\epsilon_r = 3.17$. This simplifies the transformation of delay time to ice thickness. Snow is different in that the density and water content varies.

Studies of snow cover have been performed with various electromagnetic methods such as spectrometers, microwave radars and gamma-ray measurements. All these methods can be used from airborne platforms.

The spectrometers measure the brightness temperature T_b which decreases exponentially with the equivalent water content of the snow cover. Liquid water produces a sharp increase in the brightness temperature. The penetration is around 10 - 100 times greater the wavelength, FOSTER *et al* 1980.

For microwave radars the measured parameter is the back-scatter coefficient σ_0 , which increases exponentially with

the equivalent water content of snow. It also increases with the amount of free water, STILES, ULABY and RANGO 1981.

The gamma method is based on the attenuation in the snow cover of natural gamma radiation from the ground. This method is not sensitive to free water and gives a measure of the equivalent water content in the snow cover. Since the snow attenuates the radiation the maximum detectable equivalent water content is limited by the background radiation. Maximum values reported are 0.4 - 0.6 m equivalent water content, with an error of less than 10 % for values less than 0.3 m, DAHL and ØDEGAARD (-).

These methods all permit measurements to be taken from aircrafts and thus give very good coverage capacity but bad resolution. Impulse radar is proposed as a method to use for small-scale, detailed study of the snow cover. This may yield important ground-truth data which is used as input for more superficial surveys and for hydrological models, provided the density variations can be neglected.

Mathematical Formulations

Consider a cube of freshly fallen snow with a volume of 1 m^3 and a density of 100 kg/m^3 , that is compressed until it reaches the density of ice, 920 kg/m^3 , while the bottom surface is maintained at 1 m^2 .

While the compression takes place a radar antenna lying on top of the snow transmits pulses that are reflected against the underlying material. The two-way reflection time, twt, can be written

$$\text{twt} = \frac{2 \cdot h}{v} \quad (3.1)$$

where

h = the height of the cube

v = the radiowave velocity of snow

Since the weight of the snow is constant, the height, h , of the cube can be expressed as a function of the density, γ

$$h \cdot \gamma = \text{constant} \quad (3.2)$$

In this example the height can be expressed as

$$h = \frac{100}{\gamma} \cdot 1.0 \quad (3.3)$$

If x is taken as the ratio of the density of snow to that of ice, (3.3) can be rewritten as

$$h = \frac{100}{920 \cdot x} \cdot 1.0 \quad (3.4)$$

GLEN and PAREN 1975 have made a survey of different ways to calculate the velocity of radiowaves in snow. The radiowave velocity, v , is generally expressed as the relative permittivity, ϵ_r , of the material in question

$$\epsilon_r = \left(\frac{c}{v}\right)^2 \quad (3.5)$$

where

ϵ_r = relative permittivity (-)

c = radiowave velocity, in vacuum ($3 \cdot 10^8$ m/s)

v = radiowave velocity in the material

They found that the model of Looyenga was easy to use and gave good results. Looyenga's equation has the following form for snow, considered as a mixture of ice and air

$$\epsilon_{rs}^{\frac{1}{3}} - 1 = x(\epsilon_{ri}^{\frac{1}{3}} - 1) \quad (3.6)$$

where

ϵ_{rs} = relative permittivity of snow

x = ratio of the density of snow to that of ice

ϵ_{ri} = relative permittivity of ice

If the dielectric loss tangent is small and the frequency is high we may use a real form for expressing ϵ_{ri} . With $\epsilon_{ri} = 3.17$ (3.6) can be written as

$$\epsilon_{rs} = (1 + 0.469 \cdot x)^3 \quad (3.7)$$

By using (3.5) we derive an expression for the radiowave velocity in snow which is

$$v = \frac{3.0 \cdot 10^8}{\sqrt{(1 + 0.469 \cdot x)^3}} \quad (3.8)$$

and we can then calculate the two-way reflection time, twt, by using (3.1)

$$\text{twt} = \frac{2h}{v} = \frac{2 \frac{100}{920x} \cdot 1.0}{\frac{3.0 \cdot 10^8}{\sqrt{(1+0.469x)^3}}} = \frac{200 \sqrt{(1 + 0.469x)^3}}{920x \cdot 3.0 \cdot 10^8} \quad (3.9)$$

This relation is plotted in Figure 3.1, and shows that the reflection time strongly depends on density at low density values, but that it becomes rather independant at higher values of density.

Another way of expressing this is that for densities greater than about 300 kg/m^3 the reflection time will describe the amount of ice in the snow cover, i.e. the water equivalent.

Although the distance the wave has to travel becomes shorter when the snow pack is compressed, the delay times remains rather constant, since the radiowave velocity decreases when the density increases. The two effects tend to balance each other but not completely.

Another favourable circumstance is that the snow is layered. The average density in a layered snow pack will probably show less variation than the density as a function of depth will.

In Figure 3.2 the losses in a snow water mixture are presented for two snow densities. For dry snow the losses are very small but the addition of a small amount of water gives a steep increase in attenuation, CUMMING 1952.

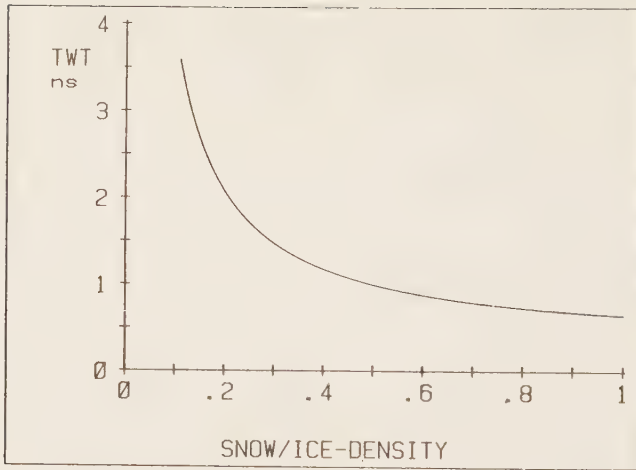


Figure 3.1. The two-way reflection time in an original snow pack of 1.0 m as density is increased from 100 to 920 kg/m^3 .

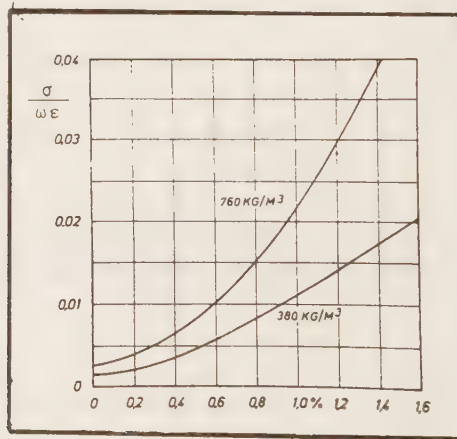


Figure 3.2. Loss tangent of a snow-water mixture at 0°C measured at 9.375 MHz versus water content expressed in percent by weight. The parameter is the snow density. [CUMMING 1952.]

It is thus concluded that free water is hazardous to the quality in impulse radar determination of equivalent water content since it strongly changes the electrical parameters of the snow.

Experiments

Field tests were performed south of Kultsjön in Västerbotten in late March 1982. The area is a hydrological test site and gamma-ray measurements have been taken for some years.

The radar equipment was installed in the weatherproof cabin of a tracked snow vehicle. Power was taken from a 2 kW gasoline generator placed outside the cabin. Figure 3.3 shows the radar equipment inside the cabin and Figure 3.4 presents the vehicle.

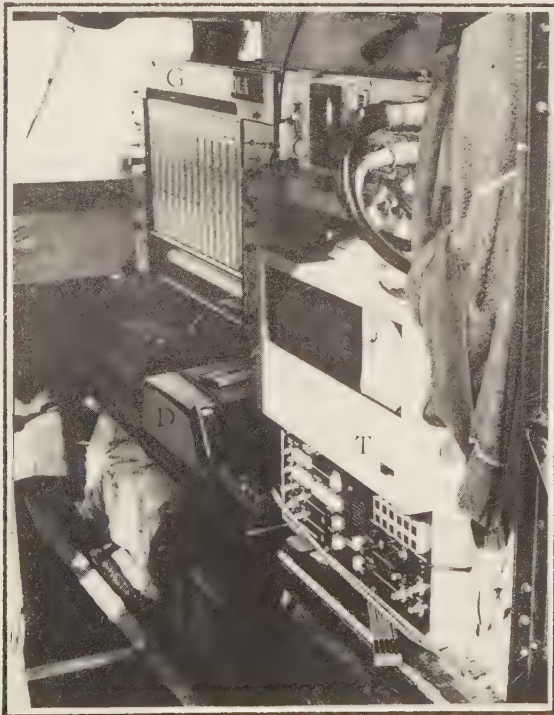


Figure 3.3. Radar equipment installed in the cabin of the snow vehicle. C = control unit, T = tape recorder, G = graphic recorder and D = digital computer.



Figure 3.4. The snow vehicle that was used. G = Generator and A = 900 MHz antenna.

Several tests with various antennas and antenna arrangements were performed along two profiles presented in Figure 3.5. These tests led rapidly to the conclusion that a 900 MHz antenna attached to a cantilever and situated 0.5 m above the snow surface gave the best results. A typical digitized radar return signal is presented in Figure 3.6. If the antenna had been elevated about 0.2 m higher it would have been possible to separate the return from the snow surface and the transmission leakage into the receiver. The maximum reflectivity for dry snow can never be larger than the reflectivity of dry ice. If the measured energy in the snow surface return is larger than this value there must be free water in the snow. The reflectivity can thus be used to determine the density of dry snow and the water content of a temperat snow cover in the snow surface.

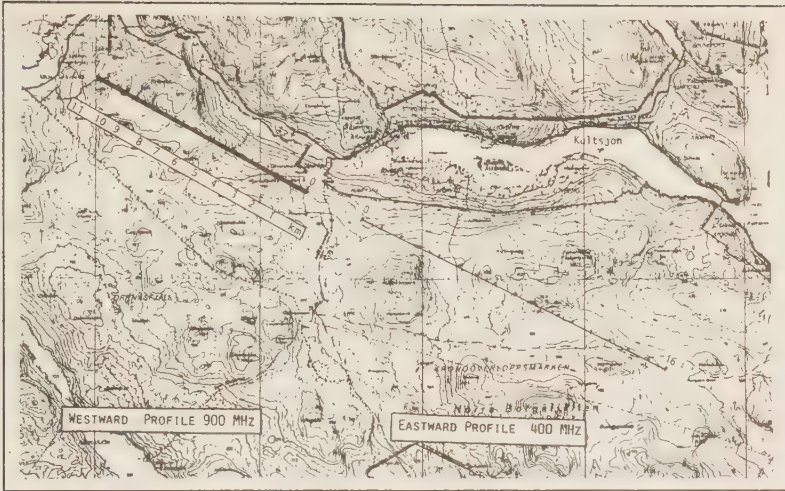


Figure 3.5. The test area south of Kultsjön in Västerbotten, 200 km northwest of Vilhelmina Profiles, lies at an elevation of 900 - 1000 m.

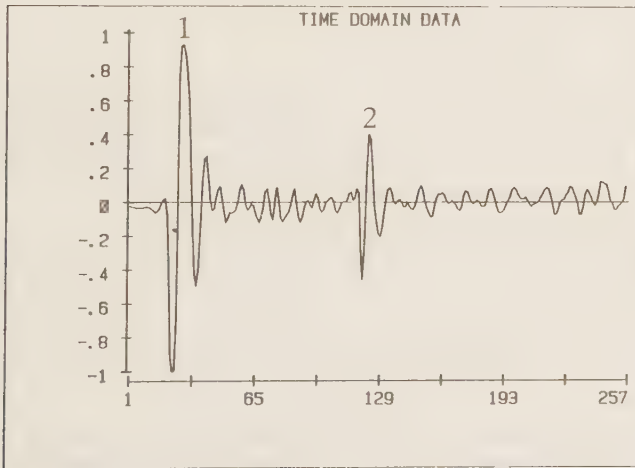


Figure 3.6. A digitized radar return. 1 = interfering transmitted impulse leaked into the receiver and snow surface return and 2 = return from the interface snow-underlying ground.

The results presented here were achieved in the western, 10 km long profile in Figure 3.5.

Proceeding the radar profiling snow sampling and snow probing were performed by skilled personnel from SMHI who operated a snow scooter.

The sampling was performed with a hollow brass cylinder $\varnothing 38$ mm which was forced through the snow cover down to the ground surface. An edge helped the cylinder cut through ice layers. By measuring the thickness of the snow cover and the weight of the snow inside the cylinder the equivalent water content and vertical average of the snow density could be calculated. Remnants of plants or soil in the edge proved that the sampling was successful.

Probing was performed by using a steel rod which was forced into the snow cover until it came against the presumed frozen soil. Thin brass rods are not sturdy enough to penetrate the ice layers that develop in the snow in mountain ranges. There is no way to assure that the rod actually reaches the ground surface.

Sampling was performed at 1 km intervals for the first eastern 5 km of the profile. The last 5 km were sampled at 250 m intervals. The entire profile was probed at 50 m distances unless a sample was taken in that point.

The radar measurements were continuous but the vehicle was stopped when a sampled point was approached. The exact sample point was marked with a signal and the antenna was placed above the signal which was then removed. Probing points were not marked. With the vehicle at rest a part of a continuous radar record was recorded in order to determine the delay time. Knowledge of the delay time and the equivalent water content at many points make it possible to determine the relation between delay times and equivalent water content. This relation can then be used to determine the

equivalent water content at any point along the profile. Also the relation between snow thickness and delay time can be established.

Results

Snow sampling and accurate return delay determinations were successfully performed in 25 points. From the obtained values the distribution of densities and equivalent water content values is determined and presented in Figure 3.7 and Figure 3.8.

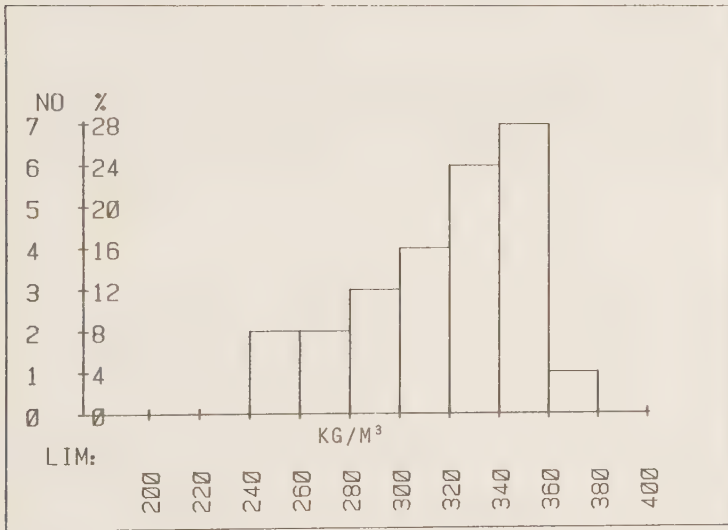


Figure 3.7. Distribution of snow densities as determined from snow sampling in the western profile.

Evidently the majority of the densities are higher than 300 kg/m^3 which is believed to be the lower "success limit" of the radar method. The average snow density is $317.2 \pm 34.8 \text{ kg/m}^3$.

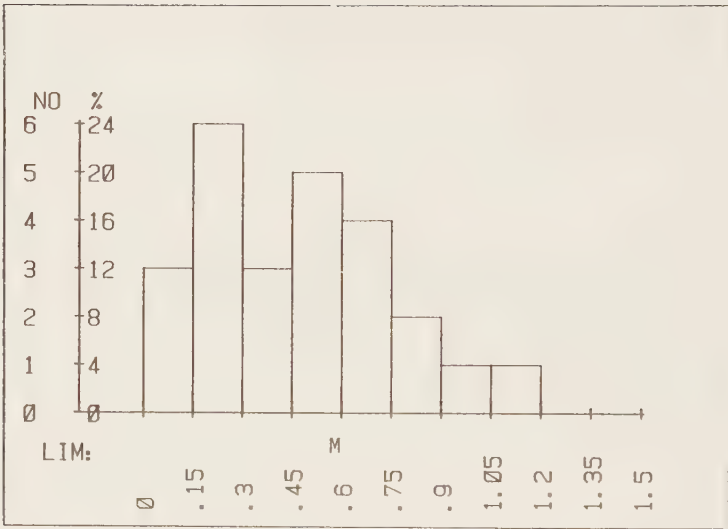


Figure 3.8. Distribution of equivalent water content as determined from snow sampling in the western profile.

The average equivalent water content is 0.461 ± 0.297 m.

In Figure 3.9 a part of the continuous radar record is presented together with the interpretation of the interface snow ground. For comparison the same part of the profile as it appears from snow probing is presented in Figure 3.10. Since no signals were placed at the probing points there may be some off-set between the two profiles.

Although the snow probing fails to detect much of the variation in the snow cover it is expected to give correct average values if no ice layers are mistaken for being the ground surface.

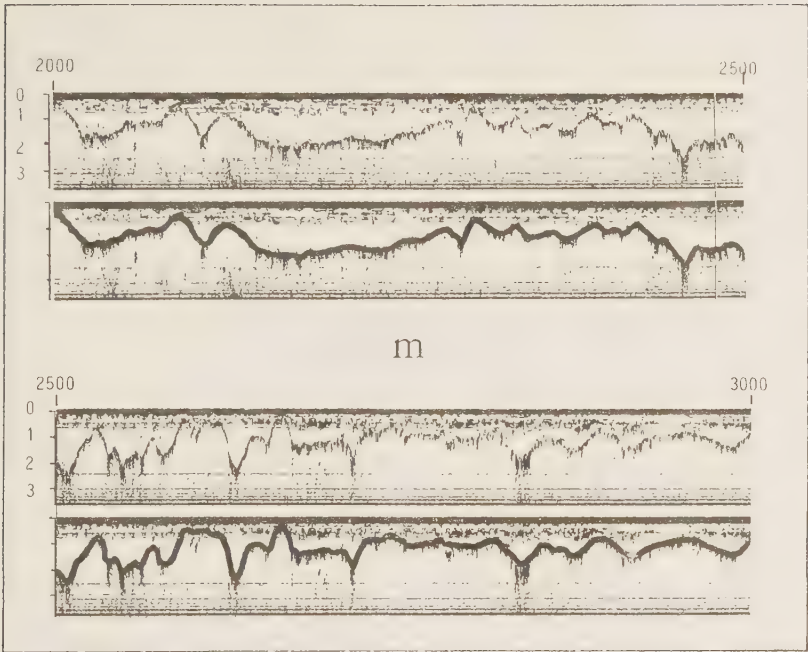


Figure 3.9. Continuous radar record. Upper profile in each pair original real time data. Lower profile with interpreted snow/ground interface that has been enhanced with a pen.

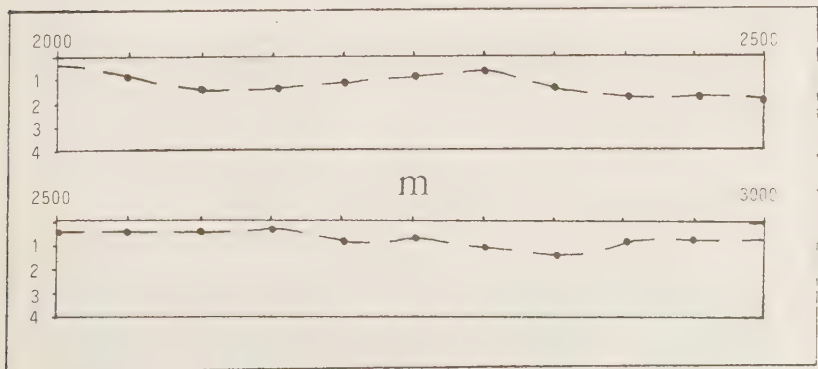


Figure 3.10. The same profile as it appears from the snow probing at 50 m intervals.

In Figure 3.11 the equivalent water content values are plotted as a function of radar delay times together with a linear regression analysis. A similar plot cannot be done for snow probing versus snow sampling since these were never performed at the same location. The accuracy of the snow probing method is therefore unknown.

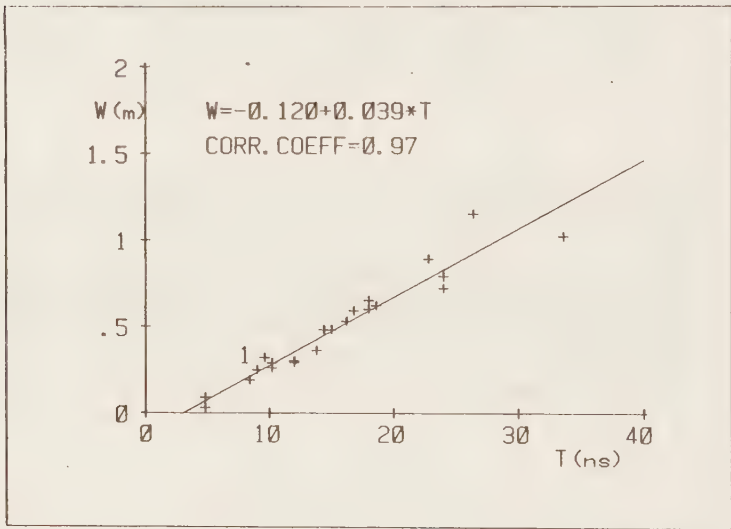


Figure 3.11. Equivalent water content values, W , as a function of radar delay times, T , and the regression line obtained with linear regression.

If W is the equivalent water content measured in metres and T is the delay time measured in nanoseconds, the relation is

$$W = -0.120 + 0.039 \cdot T \quad (3.10)$$

with the correlation coefficient $r = 0.97$.

The constant term is caused by the airflight time of the radar impulse. Delay times longer than 20 ns, which are in minority, obviously give less accuracy for a one-point estimate. Since the residuals at longer delay times seem to

differ at random one may expect average equivalent water content values to be correct.

Figure 3.12 presents snow thickness, Z , as a function of radar delay times, T , together with a linear regression analysis.

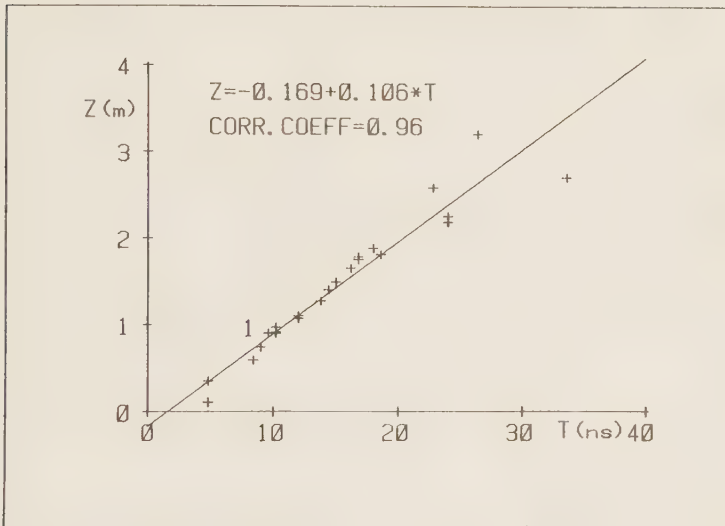


Figure 3.12. Snow thickness, Z , as a function of radar delay times, T , and the regression line obtained with linear regression.

The relation obtained is

$$Z = -0.169 + 0.106 \cdot T \quad (3.11)$$

with the correlation coefficient $r = 0.96$.

In order to evaluate the continuous radar record it has to be digitized. As seen from Figures 3.9 and 3.10 it is essential that the continuous profile is sampled close enough so that the majority of interesting information is preserved. The method for solving this problem is spectral analysis

with the Fast Fourier Transform (FFT). In order to use this method the concept of frequency and wavelength is transformed from time domain to spatial domain.

The wavelength, λ , is now a measure of the variation of the snow cover. If it varies like a sinusoid for a distance of 10 m with one maximum and one minimum the snow cover is said to have the wavelength of 10 m. Here the frequency is the rate of change and is proportional to the inverse of the wavelength.

In order to do a FFT the data must be in digital form! To avoid this circular problem one representative part of the radar profile, as presented in Figure 3.9, is digitized at "overkill". Digitizing was performed in 256 points along the 1000 m long part of the profile, i.e. at less than 4 m intervals. The result of the FFT is presented in Figure 3.13.

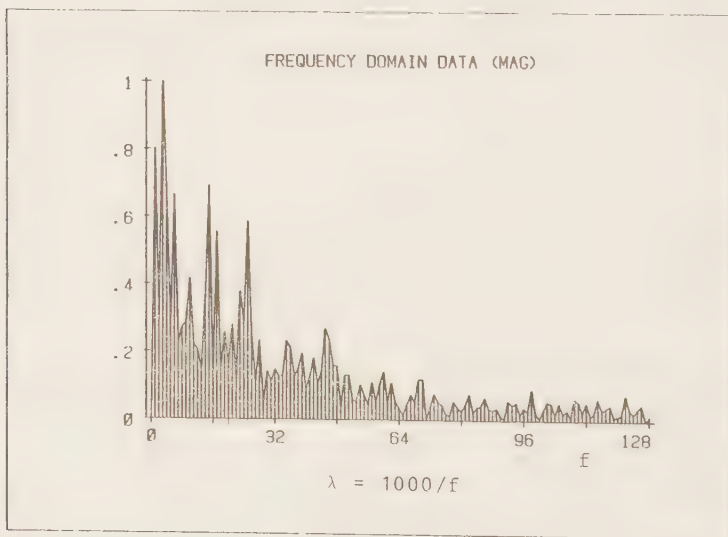


Figure 3.13. Spectral density of the snow cover along the profile in Figure 3.9. The DC-term is set to zero but was originally 5 times as strong as the strongest peak in this spectrum. Division of 1000 m by the frequency at the horizontal axis gives the wavelength.

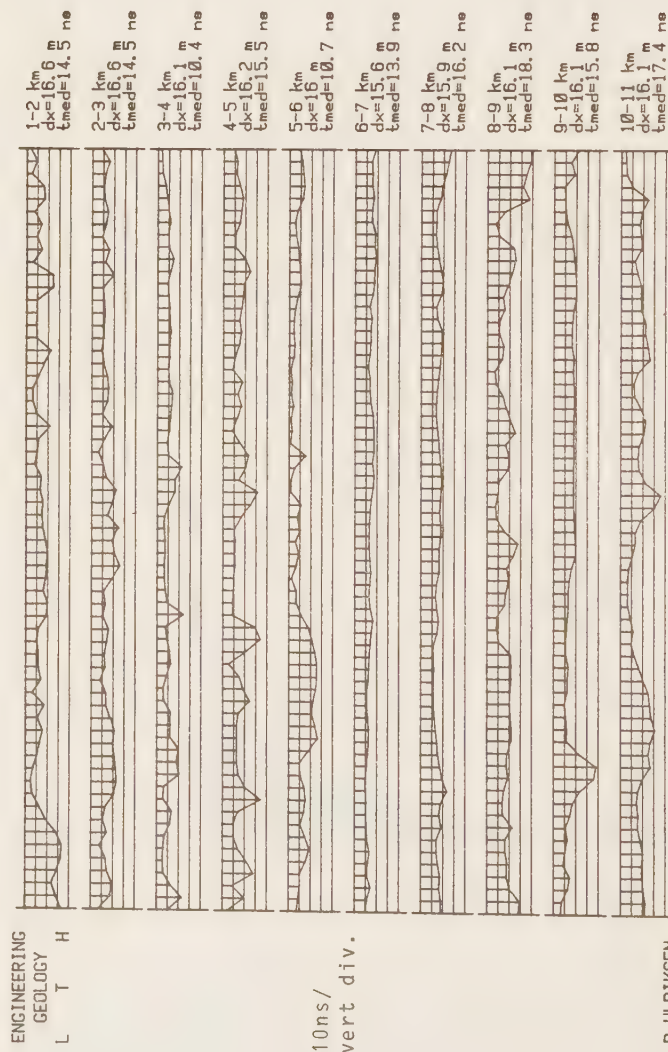
From this oversampled spectral analysis it is concluded that the majority of the variation has a wavelength longer than 20 m and the last peak is produced by a wavelength of 40 m. Sampling must be performed at half the desired minimum wavelength that is to be analyzed. The DC-term corresponds to an infinite wavelength, i.e. a horizontal sheet.

To fit the employed FFT-algorithm the number of samples has to be a power of 2. 32 samples detect wavelengths longer than 64 m which is too long. 128 samples detect wavelengths longer than 16 m which are unnecessarily short. 64 samples per kilometre is chosen as an optimum. From this discussion it is clear that the snow probing performed at 50 m intervals cannot detect wavelengths shorter than 100 m. This will not affect the average value for equivalent water content calculated from snow probing and density data, since the sum of positive and negative contributions is zero. Strictly speaking only the DC-term contributes to the average values.

The 10 km of digitized radar delay times are presented in Figure 3.14. The digitized data have an average value of 14.76 ± 6.23 ns. By using (3.10) this is transformed to an average equivalent water content of 0.456 ± 0.243 m calculated for 640 points.

The snow probing data have an average of 1.423 ± 0.733 m and multiplied by the average density 317.2 kg/m^3 it gives an average equivalent water content of 0.451 ± 0.233 m.

In Table 3.1 is a presentation of average equivalent water content as calculated from the three different methods.



RADAR ECHO-SOUNDING OF SNOWCOVER, REFLECTION TIMES

Figure 3.14. Digitized radar delay times along the western profile. 64 samples per kilometre.

Table 3.1. Average equivalent water content along the western profile calculated from snow sampling, snow probing and radar return delays.

Method	Number of samples	Average equivalent water content (m)	Standard deviation (m)
Snow sampling	25	0.461	0.297
Snow probing	200	0.451	0.233
Radar returns	640	0.456	0.243

Obviously the two latter methods depend on the first but they are equal in quality. It is interesting to note that the radar returns give an average equal water content that lies between the value of snow sampling and snow probing, though the difference is very small.

In order to compare the methods more in detail, the average water equivalent of the snow cover is calculated for 1 km parts of the 10 km long profile. Input parameters are the average density and the linear relation (3.10). The result is presented in Table 3.2 and Figure 3.15.

Due to the way these values are calculated local variations in snow densities may affect the result of both methods explaining part of the differences.

Theoretically (3.8) can be used to determine the equivalent water content from density and radar delay time. The average density is 317.2 kg/m^3 and the average delay time is 14.76 ns, but must be corrected for the air flight time which is calculated to be 1.6 ns by setting $z = 0$ in (3.11)

$$v = \frac{3.0 \cdot 10^8}{\sqrt{(1 + 0.469 \cdot \frac{317.2}{920})^3}} = 2.40 \cdot 10^8 \text{ m/s} \quad (3.8)$$

$$z = v \cdot T/2 = 1.63 \text{ m}$$

$$W = z \cdot \frac{317.2}{920.0} = 0.56$$

Table 3.2. Equivalent water content calculated for 1000 m intervals from snow probing and radar returns.

Segment (km)	Average equivalent water content from			
	Snow probing		Radar returns	
	Z(ns)	W(m)	T(m)	W(m)
1 - 2	1.46	0.464	14.5	0.446
2 - 3	1.25	0.397	14.5	0.446
3 - 4	1.04	0.328	10.4	0.286
4 - 5	1.25	0.397	15.5	0.485
5 - 6	1.07	0.340	10.7	0.297
6 - 7	1.31	0.414	13.9	0.422
7 - 8	1.54	0.488	16.2	0.512
8 - 9	1.64	0.521	18.3	0.594
9 - 10	1.69	0.535	15.8	0.496
10 - 11	1.99	0.631	17.4	0.559

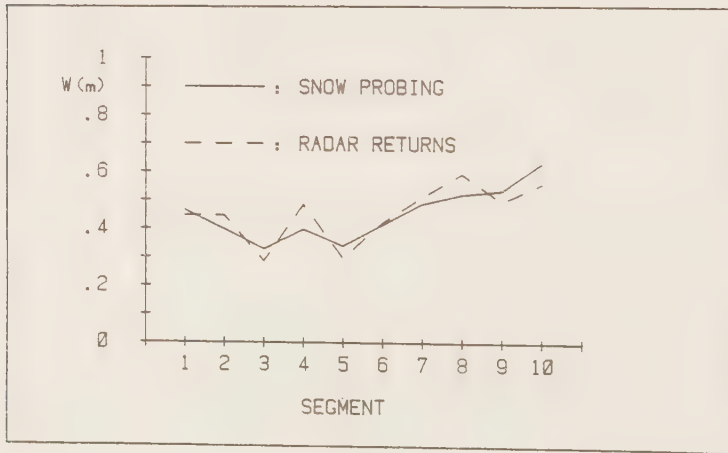


Figure 3.15. Equivalent water content values along the 10 km long profile calculated for 1 km segments. For snow probing a density of 317.2 kg/m^3 is used for radar return delays (3.10).

This value is so much greater than the value found using the previous methods that (3.8) cannot be recommended for calculation of equivalent water content.

To use the available information from density variations along the profile the following method can be applied. The first step is to determine the average density for each 1 km segment. Then use the average snow depth obtained from snow probing and from (3.11) to calculate the average equivalent water content of the snow cover. The data and results are presented in Table 3.3 and Figure 3.16.

Table 3.3. Equivalent water content calculated for 1 km segments from snow probing and radar delays. The average density in each segment and (3.11) is used to determine snow thickness from radar delays.

Segment (km)	Density (kg/m ³)	Number of density observations	Average water content from			
			Snow probing Z (m)	Radar returns W (m)	T (ns)	W (m)
1 - 2	330.8	2	1.46	0.483	14.5	0.453
2 - 3	321.0	2	1.25	0.401	14.5	0.439
3 - 4	381.0	2	1.04	0.396	10.4	0.356
4 - 5	372.5	2	1.25	0.466	15.5	0.549
5 - 6	310.6	5	1.07	0.332	10.7	0.300
6 - 7	320.0	5	1.31	0.419	13.9	0.417
7 - 8	329.1	5	1.54	0.507	16.2	0.510
8 - 9	279.1	5	1.64	0.458	18.3	0.494
9 - 10	337.7	5	1.69	0.571	15.8	0.509
10 - 11	336.1	5	1.99	0.669	17.4	0.563

Comparing Figures 3.15 and 3.16 does not give any visual preference for either method. Summing the differences segment for segment shows that in the first method the radar overestimates the equivalent water content with 2.8 mm while the latter method underestimates with 11.2 mm relative to snow probing, which method is not to be considered exact. Since the first method is easier to operate and more direct it is recommended for future use.

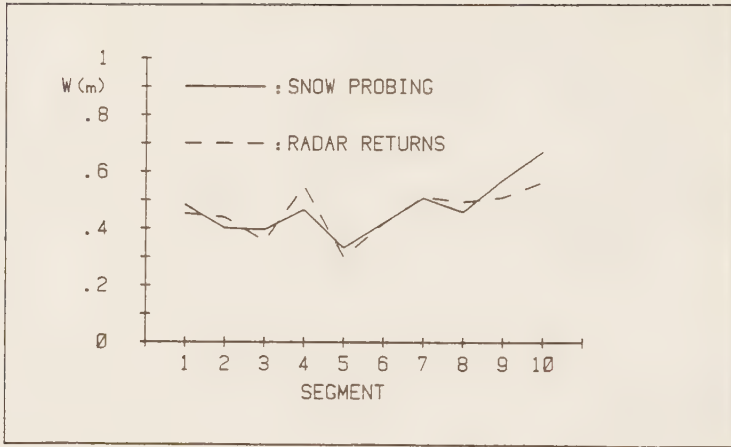


Figure 3.16. Equivalent water content calculated for 1 km segments from snow probing and radar delays where the average density in each segment and (3.11) is used to determine the snow thickness from radar delays. Segment 1 corresponds to 1 - 2 km in the profile.

The possibility to calculate the water content spectrum has already been discussed. Another feature of interest is the water content distribution, i.e. how many per cents of the snow cover have an equivalent water content between, let us say, 0.2 - 0.4 m. In Figures 3.17 and 3.18 are presentations of water content spectra for 32 frequencies and water content distribution for 20 classes. Each frame is valid for a 1 km long segment of the 10 km long profile. The spectra now include the DC-term to the left. The relation between the strength of this term and that for higher frequencies may be interpreted as the relation between the volume of snow in a horizontal sheet and the volume of snow in the canyons that are passed. A completely flat surface with a smooth snow cover would only produce a DC-term and no higher frequencies.

Another way to present the water content distribution is to accumulate the values and to present them as percentages being less than a certain value. This is done in Figure 3.19.

This information may be used in various ways. If the snow lies like a sheet or lies in canyons is likely to affect the melt-off process. The snow distribution is important for evaluation of some gamma-ray measurements, and also for forecasting the run-off.

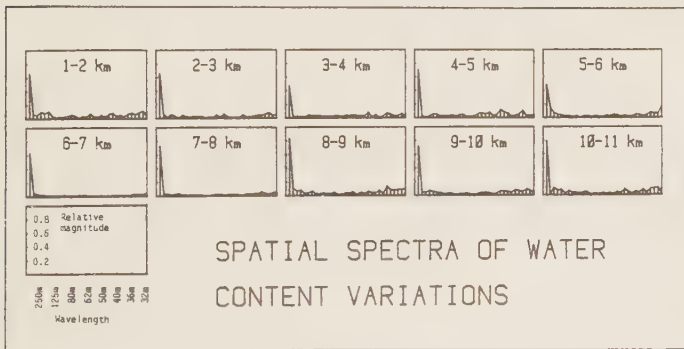


Figure 3.17. Spectra of water content variations for ten segments along the profile.

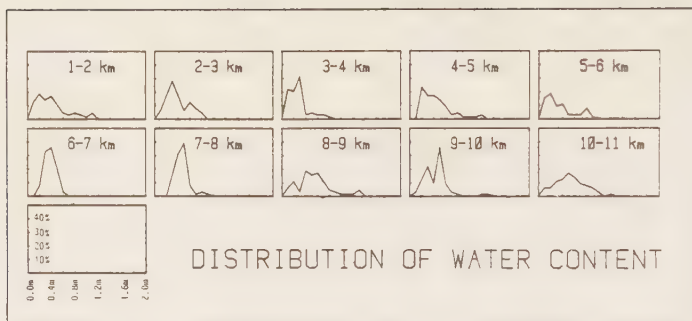


Figure 3.18. Distribution of the water content for ten segments along the profile.

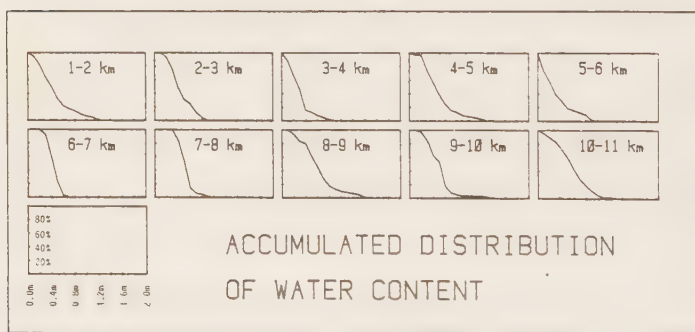


Figure 3.19. Accumulated distribution of water content for ten segments along the profile.

Finally the entire profile is plotted, in Figure 3.20, as it appears from the digitized radar records and from the snow probing.

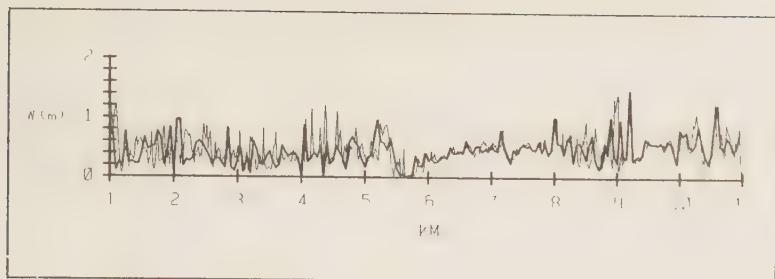


Figure 3.20. The equivalent water content of the snow cover as it appears from radar records (thin line, 640 points) and as it appears from snow sampling (thick line, 200 points).

Concerning the accuracy of the proposed method it may be worthwhile to study how the average water content along a profile is calculated. If $W(T)$ is a function of time such as in (3.10) and $T(x)$ is the radar delay time at any point x along the profile, the the average water content W_a is calculated according to

$$W_a = \frac{1}{L} \int_0^L W(T(x)) dx \quad (3.12)$$

Since $W(T)$ is a linear function (3.12) can be expressed as

$$W_a = W \left[\frac{1}{L} \int_0^L T(x) dx \right] \quad (3.13)$$

It is now clear that the accuracy of the method depends on two independant properties $W(T)$ and $\int T(x) dx$. The accuracy of $W(T)$ depends on the number of snow samples and $\int T(x) dx$ is exact. This is a fundamental difference from snow probing

which only yields an estimate of the snow thickness along the profile. Citing GOODISON, FERGUSON and McKAY in Handbook of Snow 1981, page 259:

"Frequently an investigator will find that depth influences the value of the (average) water equivalent much more than density. In this situation the number of depth samples should be increased relative to the number of density samples."

If the relation between water content in the snow cover and the radar delay times is normally distributed it is in principle possible to calculate the number of samples necessary to obtain a certain accuracy for $W(T)$. Note that this number is only dependant on the distribution, not on the number or length of profiles recorded in an area. Of course the variance may increase if the area is extended.

If the constant term in (3.10) is considered a system parameter the variance lies in the linear term, here called C . If C is normally distributed then the true value of C lies between $\bar{C} \pm (\sigma_C/\sqrt{N}) \cdot t$, where $\bar{C}$ is the mean value, σ_C is the standard deviation and t is the "Student's t ", which is dependant on confidence level and sample size. In Figure 3.21 $t/\sqrt{N}$ is plotted as a function of degree of freedom, which is the sample size minus one.

It is obvious that the accuracy always increases with the number of samples. For 95 % confidence interval additional samples more than 40 becomes very costly and for 99.9 % confidence interval the same is true for about 60 samples. Considering the overall complexity of hydrological modelling it may not be worthwhile to obtain more than 95 % confidence interval. Then using 40 samples will leave the rest of the error to the standard deviation σ_C , which is a property of the snow cover.

It may be argued that the estimate of σ , σ^* will be better if more samples are used.

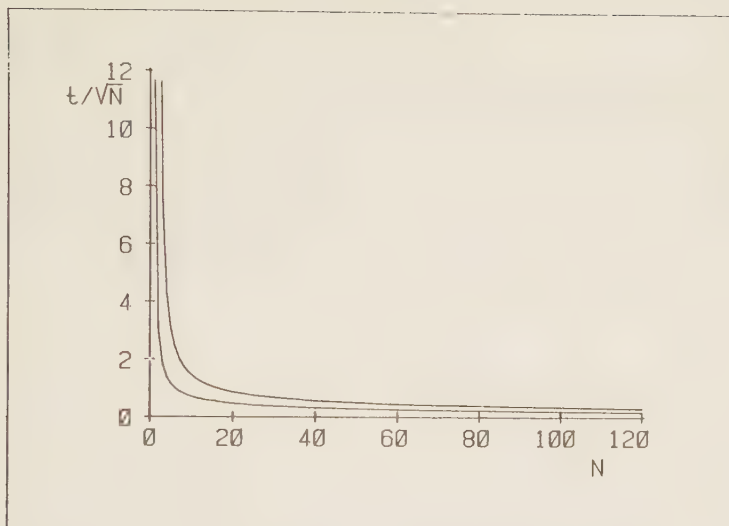


Figure 3.21. $t/\sqrt{N}$ as a function of degree of freedom for 95 % and 99.9 % confidence levels. 99.9 % is the upper curve.

It is possible to estimate $\bar{C}^*$ and σ_C^* in the experiment from the 25 samples obtained. In order to eliminate the airflight time a delay T_a is calculated, from (3.10), setting $W(T) = 0$, which is subtracted from the delay times.

$$W(T_a) = -0.120 + 0.039 \cdot T_a = 0 \quad (3.10)$$

$$T_a = 3.07 \text{ ns}$$

Then the measured water content is divided by the corrected delay time and the mean and standard deviation calculated.

The result is that $\bar{C}^* = 0.038$ and $\sigma_C^* = 0.008$. With the use of the 25 samples the 95 % confidence limit for C is $0.038 \pm 0.008 \cdot 2.064/\sqrt{25}$ or 0.038 ± 0.0033 , i.e. there is less than 9 % error.

If it is assumed that σ^* is correct, 40 samples would give a 95 % confidence interval of $0.038 \pm 0.008 \cdot 2.023/\sqrt{40}$ or

0.038 ± 0.0026 , i.e. less than 7 % error. To decrease the error further would be very expensive.

Certainly $W(T)$ is influenced by the season. It seems reasonable that the average density in the snow cover at a certain location is proportional to the water content and to the time of the year. Since the water content increases as a function of time until the melt-off begins, Figure 3.22, $W(T)$ may actually be a two-dimensional variable of time $W(T_r, T_s)$ where T_r is radar delay time and T_s is seasonal time.

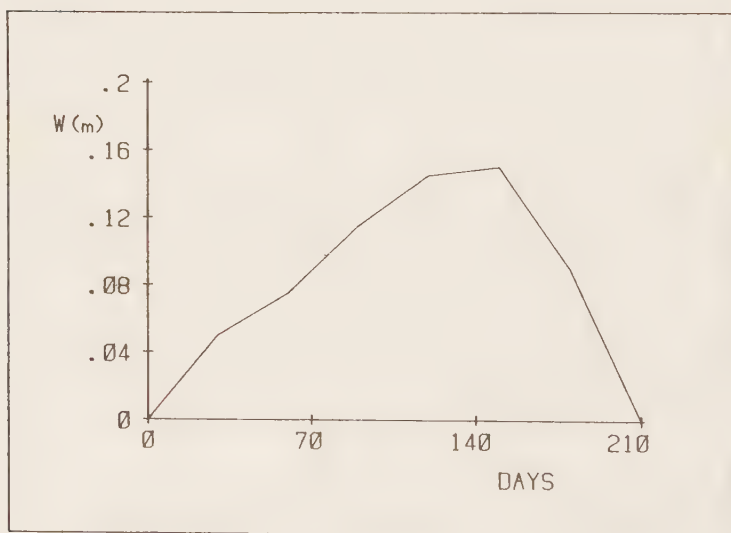


Figure 3.22. Development of the water content as a function of time in days starting on December 15, Boise River Basin, Idaho. [HANDBOOK OF SNOW 1981.]

Because the water content also increases as a function of the elevation E . Figure 3.22, W might even be a three-dimensional function $W(T_r, T_s, E)$.

It is likely that the dependence of this function on T_s will be related to the meteorological history of the surveyed area.

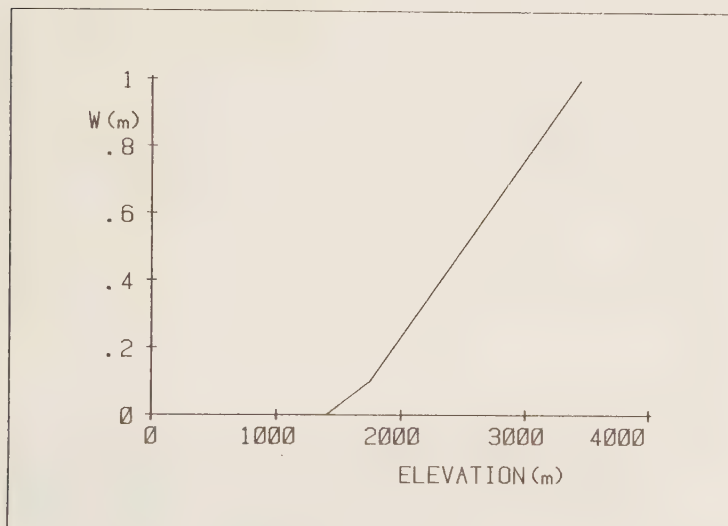


Figure 3.23. Increase of water content in snow as a function of elevation. Kzyleha River USSR 1953. [HANDBOOK OF SNOW 1981.]

Conclusion

Impulse radar at a center frequency of 900 MHz has proven capable in determining the equivalent water content of the snow cover together with a few snow samples. It is recommended that the relation between water content and radar delay time is established with linear regression and that about 40 samples is a cost-efficient number. It is believed that this relation is dependant on the elevation and the meteorological history of the surveyed area. Best results are expected late in the season, before the snow starts to melt.

4 MEASUREMENTS ON ROADS

Previous Work

Impulse radar has been used by MOORE *et al* 1980 and by STEINWAY *et al* 1981 to detect voids under concrete pavements. Their experimental results indicate that the amplitude of the returns is proportional to the void thickness until this is so large that the reflections from concrete/air, air/underlying soil are separated in which case the separation is proportional to the void thickness, Figure 4.1. Automatic computer algorithms were used to determine void size from radar returns. High moisture content and temperature appear to make the measurements difficult since it changes the relative permittivity of concrete and the noise level in the receiver. Measurements made at less than 21°C resulted in excellent void location and sizing estimates.

Bruch 1981 made surveys of asphalt thickness where subsidence had been overcome by successive layers of asphalt. The method gave real time registrations up to the maximum asphalt thickness of 1.75 m. The operation was carried out on a highway at rush-hour with very little disturbance of the circulation. A profile showing thickness variations is presented in Figure 4.2.

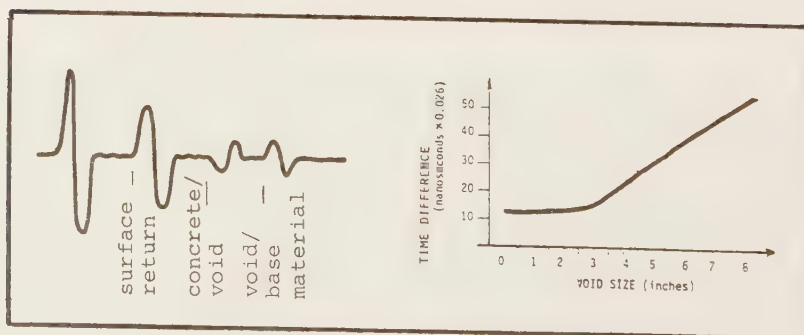


Figure 4.1. Detection of void thickness. Cont. next page.

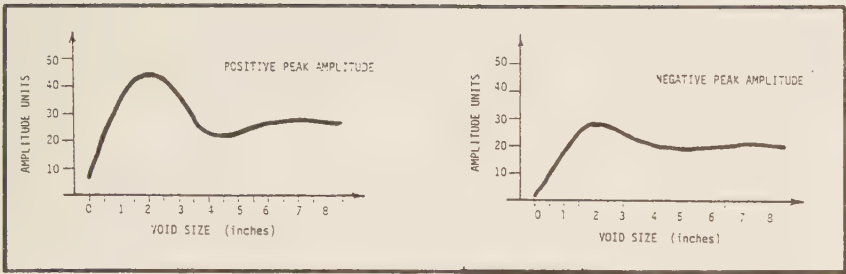


Figure 4.1. Detection of void thickness. (STEINWAY *et al* 1981.)

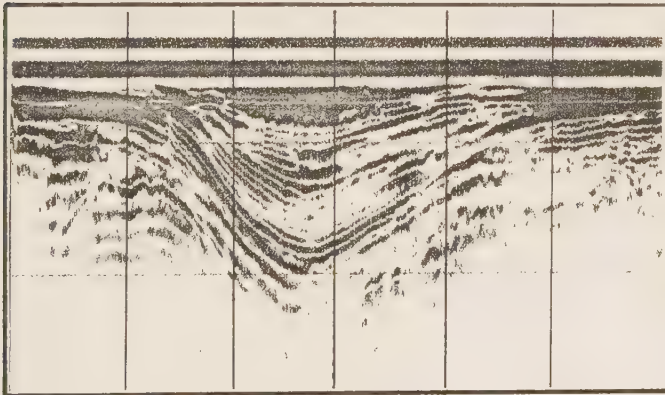


Figure 4.2. Profiling of asphalt thickness on subsided road. (BRUCH 1981.)

Detection of Salt Damages in Concrete (Pat. Pend.)

In order to prevent water from freezing on the roads in winter, salt is distributed over the pavement. It is well known that salt may create damages to concrete especially if associated with repetitive freezing and thawing. The

problem is now overcome by mixing a pore-volume increasing chemical with the concrete. For many older bridges this have not been done and damages have resulted. A well known example is Skuröbron in Stockholm where large amounts of concrete has transformed into something gravel-like with no strength whatsoever. These damages began when salt penetrated into the concrete construction.

Detection of these zones poses a major problem for highway authorities. So far the only practiced method is to drill cores out of the bridge and make a chemical analysis of the salt content relative the cement content by weight.

This method is tedious and expensive and there is also a delay between field work and the result from the chemical analysis. Furthermore each core taken decreases the integrity of the construction. If no repair of the bridge turns out to be necessary the hole will be filled with rapid hardening cement. Most likely rebars have been cut.

A low-cost method that could rapidly survey large areas and give the result in real time is therefore of great potential value for those countries where salt is extensively used on the roads in winter.

Theoretical Model

Impulse radar is proposed to be such a tool due to its capability of detecting changes in electrical parameters in a material. The two parameters of interest are the relative permittivity, ϵ_r , which is proportional to the water content of a material and the conductivity, σ , which in this case is proportional to the amount of salt in solution. Solid salt is an isolator and transparent to radar measurements.

The radar is proposed to work as a reflectometer. The reflection coefficient, r , of a material is governed by the change in impedance, Z , when the waves go from one media to another.

$$r = \frac{Z_2 - Z_1}{Z_2 + Z_1} \quad (1.13)$$

The impedance is a complex number given by

$$Z = \sqrt{\frac{j\omega\mu}{\sigma + j\omega\epsilon}} \quad (1.10)$$

The parameters σ and ϵ are listed in Table 4.1 where the impedance Z is calculated for a frequency of 900 MHz, which is the center frequency of the system-antenna giving best resolution in time.

Table 4.1. Electrical parameters in bridge construction materials.

Material	$\mu_r = \mu/\mu_0$	$\epsilon_r = \epsilon/\epsilon_0$	σ (mho/m)	Z (ohm)
Air	1	1	0	377
Water, pure 18°C	1	81	$3.7 \cdot 10^{-6}$	42
Strong concrete				
- Dry	1	6.0	$1.2 \cdot 10^{-3}$	154
- Soaked 20 hrs	1	10.9	$7.1 \cdot 10^{-3}$	114
Cracked concrete				
- Dry	1	4.5	$2.25 \cdot 10^{-3}$	177
- Soaked 20 hrs	1	13.7	$3.2 \cdot 10^{-3}$	102
Asphalt (assumed)	1	2.0	$1.25 \cdot 10^{-3}$	267

In Table 4.2 DC conductivities of different NaCl-solutions are listed. The relative permittivity is assumed to be 81 in all cases, though it decreases slightly with increasing salt concentration.

Table 4.2. DC conductivity of salt solutions.

T(°C)	0*	σ (gm salt/kg water)							
		5	10	15	20	25	30	35	40
0	1.2	.48	.92	1.35	1.76	2.16	2.54	2.93	3.31
5	2.0	.55	1.07	1.56	2.03	2.48	2.92	3.35	3.78
10	2.3	.63	1.22	1.78	2.31	2.83	3.32	3.82	4.30
15	3.1	.71	1.38	2.01	2.61	3.19	3.75	4.31	4.86
20	4.1	.79	1.54	2.25	2.92	3.57	4.20	4.82	5.43
25	5.5	.88	1.71	2.49	3.23	3.94	4.64	5.32	6.01
30	6.8	.97	1.87	2.73	3.54	4.33	5.10	5.85	6.60

* / $\times 10^{-6}$ (mho/m) | From "ANTENNAS IN MATTER" 1981. |

The water and the salt appear as a mixture with concrete. WIENER 1910 has presented an expression from which to calculate the relative permittivity ϵ_{rm} of a mixture. If spheres having a relative permittivity ϵ_{r1} and occupying the fractional volume p of another material which has a relative permittivity ϵ_{r2} , then ϵ_{rm} is calculated by

$$\frac{\epsilon_{rm} - 1}{\epsilon_{rm} + 2} = p \left(\frac{\epsilon_{r1} - 1}{\epsilon_{r1} + 2} \right) + (1 - p) \left(\frac{\epsilon_{r2} - 1}{\epsilon_{r2} + 2} \right) \quad (4.1)$$

An expression for the resistivity ρ of a porous media where part of the porosity is filled with water of resistivity ρ_w is given by Archie's law

$$\rho = F \cdot \rho_w \cdot q^n \quad (4.2)$$

where

$$F = a \cdot p^{-m} \quad (4.3)$$

a, m, n = empirically found parameters

p = the fractional pore volume V_p/V

q = the fraction of the pore volume filled with water V_w/V_p

F = a formation factor

The value of F as a function of a and m is presented in Figure 4.3. The parameter n lies in the range 1.3 to 2.2.

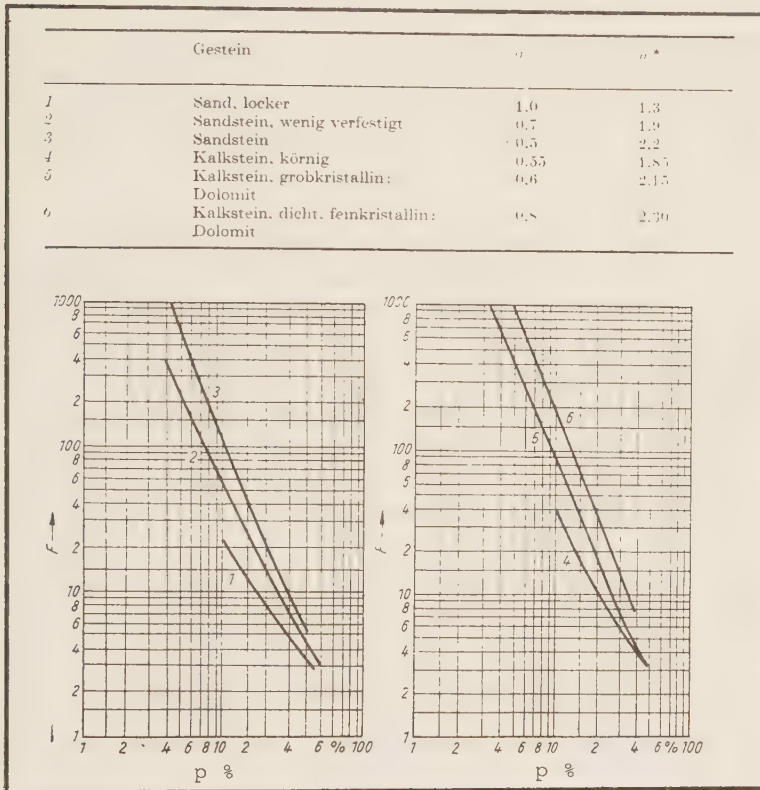


Figure 4.3. F as a function of p in % (From Angewandte Geophysik.)

To get the conductivity from the resistivity we simply invert the value

$$\sigma = \frac{1}{\rho} \quad (4.4)$$

We now have possibilities to calculate the reflection coefficient between asphalt and undamaged concrete and between asphalt and damaged concrete.

In practice two additional variables have to be considered since we are measuring in time domain. These are the thickness of the asphalt layer and the thickness of the damaged zone.

When the impulse has left the antenna there is first a delay associated with the distance between the antenna and the pavement. Then there is a delay in the asphalt and finally there is a delay in the damaged zone.

The delay in the air and in the asphalt is constant and can not produce any destructive interference but this can occur in the damaged zone. However this is not likely to happen since the skin depth in this material is very small and no energy will be transmitted through it. This condition is effectively met if the skin depth is less than 50 % of the damaged zone's thickness. In that case the impulse is attenuated to 2 % of its original value when it has passed two times through the damaged layer.

Theoretical Example

Assume the situation in Figure 4.4.

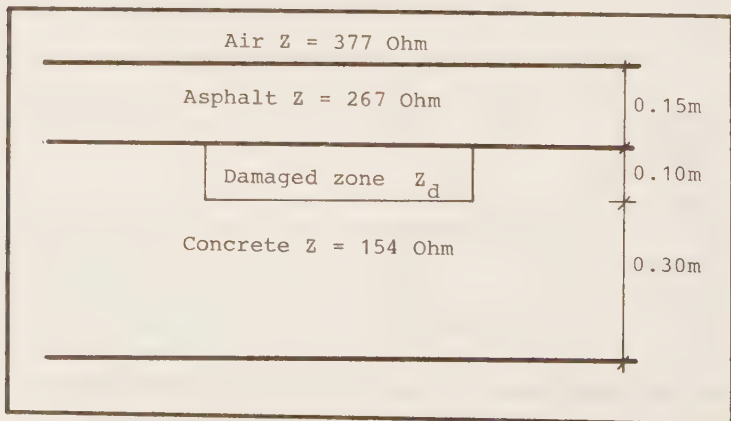


Figure 4.4. Hypothetical salt damage.

All impedances are given at 900 MHz. For the damaged zone we assume that 25 % of the pore space p is filled with a saline solution of concentration 1 % and that $p = 20$ %. The relative permittivity of the water is 81 and of the concrete 6. The resulting relative permittivity ϵ_{rm} is given by

$$\frac{\epsilon_{rm} - 1}{\epsilon_{rm} + 2} = 0.2 \cdot \left(\frac{81 - 1}{81 + 2} \right) + (1 - 0.2) \left(\frac{6 - 1}{6 + 2} \right) \quad (4.1)$$

$$\epsilon_{rm} = 7.68$$

and the resistivity is derived from Archie's law, Table 4.2, Figure 4.3 and the assumption that $n = 2$

$$\rho = 38 \cdot 0.92 \cdot 0.25^2 \quad (4.2)$$

$$\rho = 2.19 \, \Omega\text{m}$$

and the conductivity σ

$$\sigma = \frac{1}{2.19} = 0.46 \, \text{mho/m}$$

With $\epsilon_{rm} = 7.68$, $\sigma = 0.46 \, \text{mho/m}$ and $f = 900 \, \text{MHz}$ the impedance of the damaged concrete can be calculated using

$$|Z_d| = \left| \frac{j\omega\mu}{\sigma + j\omega\epsilon} \right| = 109 \, \Omega \quad (1.11)$$

$$\text{Skin depth } \delta = \frac{1}{\alpha} \quad (1.8)$$

$$\delta = 0.036 \, \text{m}$$

for a thickness d of 15 cm there will be effectively no energy transported through the damaged layer and no destructive interference will take place.

The reflection coefficient r between asphalt and undamaged concrete is

$$r_u = \frac{154 - 267}{154 + 267} = -0.27; \quad R_u = 0.073 \quad (1.13)$$

and between asphalt and the damaged zone

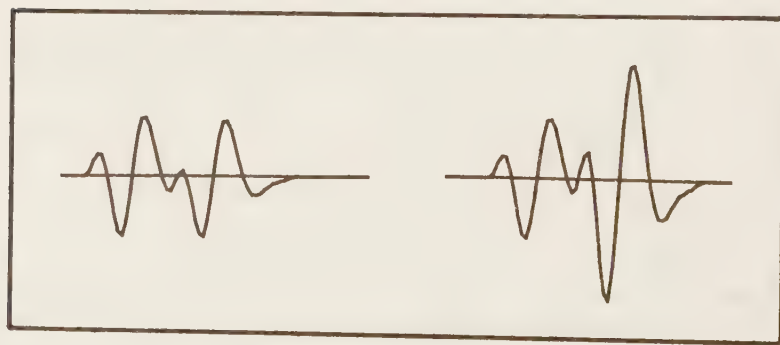
$$r_d = \frac{109 - 267}{109 + 267} = -0.42; \quad R_d = 0.176 \quad (1.13)$$

The reflection coefficient r is thus seen to increase 56 % over the salt damage.

Synthetic Radar Signal

To get an idea of the signal that can be expected a synthetic radar signal is constructed. This is done by convolution of an actual radar return from a metal sheet and the calculated sequence of reflection coefficients including the attenuation $e^{-\alpha z}$ that takes place in the different layers. The antenna is assumed to be in a position 0.6 m above the pavement and the metal sheet, $f = 900$ MHz. The properties of the target is described by Figure 4.4.

Figure 4.5a shows the convolution result for an undamaged part of a bridge and in Figure 4.5b the result above the damaged zone.



a)

b)

Figure 4.5. a) Convolution result for an undamaged part and b) for a damaged part of a bridge.

By measuring the return amplitudes it will be possible to locate a damage of the extent described.

Laboratory Measurements

To check if the radar method gives resolution in the salt range associated with damage, four concrete cubes according to Figure 4.6 were created. NaCl was dissolved in water to equal CaCl_2 at percentages 0, 0.5, 1.0 and 1.5 % weight salt relative weight cement since this is the unit used in previous chemical analysis.

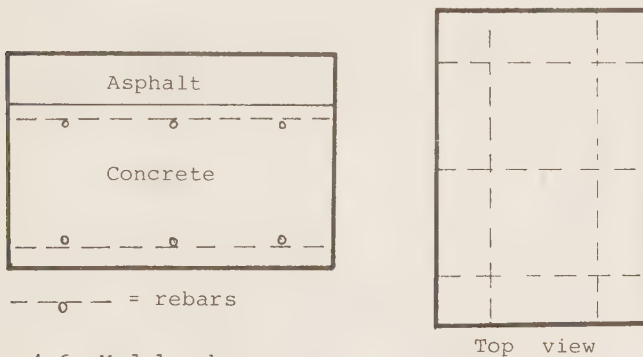


Figure 4.6. Model cubes.

Stockholms gatukontor, the road authority has found that a salt content of more than 1 % is associated with damages. After one week the cubes were sealed with epoxy resin and an asphalt top was put on, the cube now a model of a bridge.

Since the free water content in the cubes is not known it is difficult to compare this test with the theoretical example previously given.

The blocks were subsequently illuminated with the impulse radar antenna in various locations on the surface of the cube, Figure 4.7.

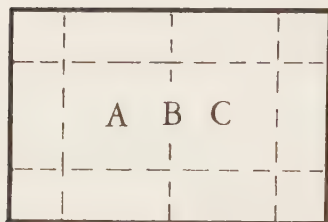


Figure 4.7. Antenna positions.

In all positions the antenna polarization was in the y-direction. The dotted lines in Figure 4.7 are the positions of rebars $\phi 10$ mm. The resulting radar signals are presented in Figure 4.8.

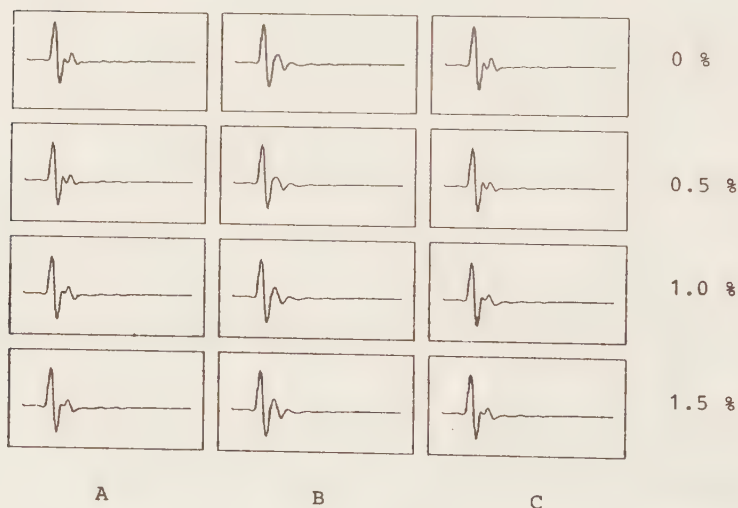


Figure 4.8. Radar returns position A - C. Percent salt relative cement by weight.

The second positive amplitude is caused by the rebars and of no interest in this case. The signal is evaluated in different ways in Table 4.3. I is the integral value of the signal between two sample numbers. The entire signal

digitized at 256 points where A is the sample amplitude gives

$$I = \sum_{j=j_0}^{j_1} |A(j)| \quad (4.5)$$

Table 4.3. Evaluation of radar returns. Reflection experiment.

Salt %	Position	$A_{\min}$	$A_{\max}$	I(32-56)	I(47-56)
0	A	-0.467	0.772	8.45	3.03
0	B	-0.483	0.772	8.81	3.32
0	C	-0.490	0.785	8.60	3.07
0.5	A	-0.654	0.785	8.92	4.39
0.5	B	-0.666	0.785	9.32	4.62
0.5	C	-0.655	0.785	8.98	4.33
1.0	A	-0.684	0.785	9.20	4.66
1.0	B	-0.684	0.785	9.38	4.84
1.0	C	-0.684	0.785	9.18	4.70
1.5	A	-0.688	0.785	9.42	4.71
1.5	B	-0.697	0.785	9.69	4.98
1.5	C	-0.660	0.785	9.20	(4.48)

Sample 32-56 contain the first two half periods of the return while 47-56 contain the second half period. The maximum positive amplitude is obviously constant and therefore only associated with the energy that leaks directly into the receiver from the transmitter. The first few half periods are named the MAIN BANG, KOERNER *et al* 1982. It consists of this energy plus the reflection from the material beneath the antenna. When using the normal recorder the Main Bang will swamp early returns and thus be destructive while when digital records are used information can be extracted. The result shows that as salt concentration increases so does the intensity of the radar return. As is expected from the constancy of $A_{\max}$ the second half period is a better indicator of salt concentration than the first and second together.

In order to see the relative effects more clearly the results are presented with all values relative to 0 % salt concentration in Table 4.4.

Table 4.4. Relative values. The antenna on the asphalt surface.

Salt %	Position	A _{min}	A _{max}	I(32-56)	I(47-56)
0.5	A	1.40	1.02	1.06	1.45
0.5	B	1.38	1.02	1.06	5% 1.39 42%
0.5	C	1.34	1.00	1.04	1.41
1.0	A	1.46	1.02	1.09	1.54
1.0	B	1.42	1.02	1.06	7% 1.46 51%
1.0	C	1.40	1.00	1.07	1.53
1.5	A	1.47	1.02	1.11	1.55
1.5	B	1.44	1.02	1.10	9% 1.50 50%
1.5	C	1.35	1.00	1.07	1.46

In Figure 4.9 is a presentation of the percentual changes in the integral values for different salt concentrations. In order to further clarify the average percentual value for positions A, B and C, written to the right in the columns in Table 4.4, is used in the diagram. The value obtained in point C at a salt concentration of 1.5 % is out-of-line and therefore care must be taken when observing the slight dip at the highest salt concentration.

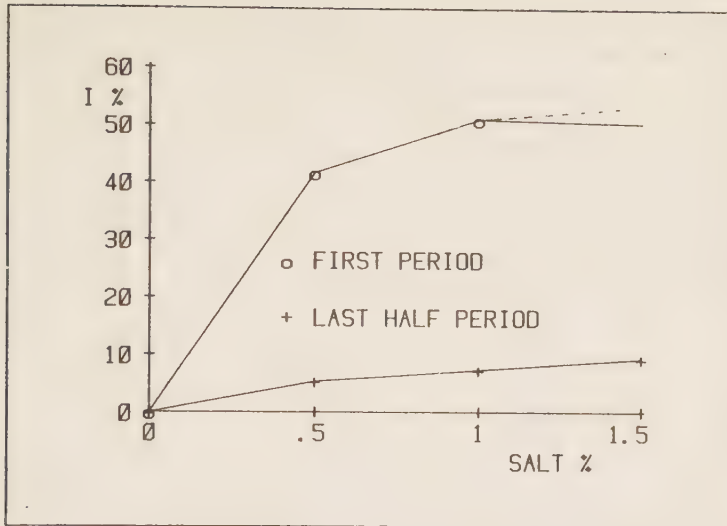


Figure 4.9. Increase of the average integral values of positions A, B and C for increasing salt concentration.

Using the symmetry around position B at the other concentrations, i.e. exchanging 1.46 for 1.55, a slight increase will be the result. This is indicated by the dotted line.

In another experiment the antenna was placed at position A and a piece of sheet metal was put beneath the cube. In this way it was possible to study the attenuation of the wave reflected against the metal, which could be regarded as a perfect reflector with $r = -1$. The radar returns are presented in Figure 4.10.

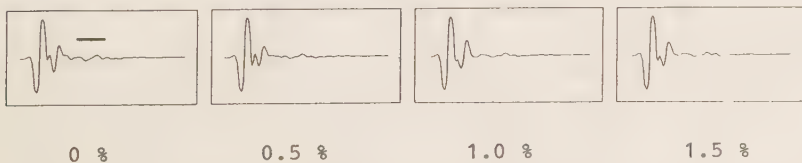


Figure 4.10. Radar returns in the transmission experiment in position A.

The returns from the metal are situated in the time period marked in the 0 % signal. It is rather difficult to distinguish in the 1.5 %-signal. The numerical results of the integration of the reflection period are given in Table 4.5.

Table 4.5. Evaluations of radar returns. Transmission experiment.

Salt %	I (95-125)	I_{rel}
0	3.99	1.0
0.5	2.91	0.73
1.0	2.61	0.65
1.5	2.67	0.67

The results show increasing attenuation with increasing salt concentration, which is to be expected. When the concentration increases from 1.0 to 1.5 % there is a slight increase in the integral value. This is above the noise level which is about 1.7. Nor can the phenomenon be attributed to the rebars in the bottom of the cubes since returns from these also must be attenuated. This effect stands unexplained. The result is presented in Figure 4.11.

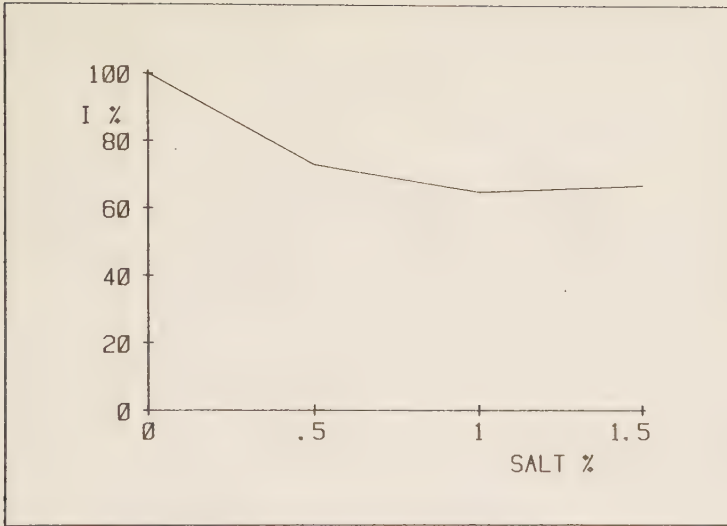


Figure 4.11. Intensity of reflected wave after reflection against a metal sheet beneath the cubes.

As with the reflection coefficients there is more resolution at the lower concentrations.

Finally the antenna was elevated 0.6 m above position B. This distance is required in order to get the reflection from the surface of the block separated from the MAIN BANG. The radar returns are presented in Figure 4.12.

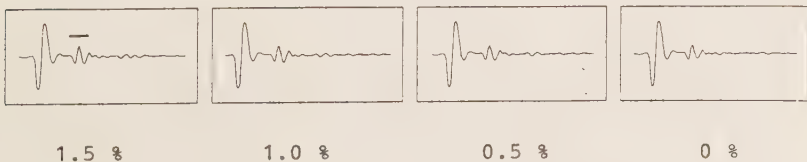


Figure 4.12. Radar returns with antenna elevated 0.6 m above position B.

The reflected wave form consists of two periods. The previous observation that the first half-period contains no

information is no longer valid since we are out of the MAIN BANG zone. In Table 4.6 the extreme values of the four half periods are presented.

Table 4.6. Results with an elevated antenna.

Salt %	1st half period		2nd half period		3rd half period		4th half period	
	A max	I	A max	I	A max	I	A max	I
0	-.48	2.32	.68	3.19	-.41	2.44	.27	1.00
0.5	-.47	2.09	.72	3.32	-.50	3.08	.28	1.17
1.0	-.52	2.41	.79	3.69	-.59	3.32	.36	1.53
1.5	-.59	2.68	.88	3.98	-.59	3.37	.30	1.17

In order to facilitate the comparison the result is also presented relative to the 0% salt concentration-values, Table 4.7.

Table 4.7. Results relative to 0% salt concentration.
Elevated antenna.

Salt %	1st half period		2nd half period		3rd half period		4th half period	
	A max	I	A max	I	A max	I	A max	I
0.5	0.98	0.90	1.06	1.04	1.22	1.26	1.04	1.17
1.0	1.08	1.04	1.16	1.16	1.44	1.36	1.33	1.53
1.5	1.23	1.16	1.29	1.25	1.44	1.38	1.11	1.17

The numerical results are displayed in Figure 4.13, from which it is obvious that the first or last half-periods are bad estimators while the second and third are good. There is a preference for the second which shows a better linearity. The first half-period is mostly associated with the reflection against the asphalt surface.

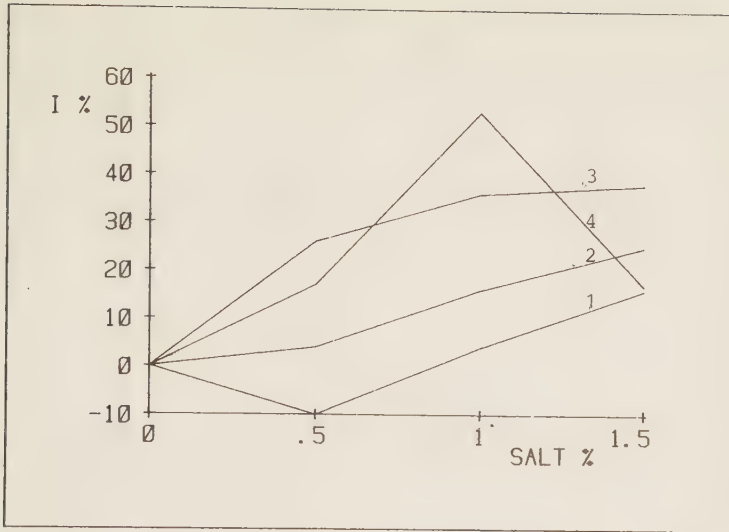


Figure 4.13. Intensity of reflected half periods 1 - 4.

The result of these laboratory experiments is that the second half period is the best indicator of salt concentration in the concrete. This fact is not general but dependant on the asphalt thickness which is obvious if the theoretical example is studied. Since the wave is attenuated severely in the damaged concrete it is also important not to integrate for a period which is too long. While the amplitude of the wave reflected at the interface between asphalt and concrete increases with salt concentration, amplitudes from reflectors inside or beneath the concrete are attenuated and if the signal is integrated for a too long period the net effect will be a constant value. The optimum seems to be to integrate the second half-period. Somewhat longer may be desirable to compensate for varying elevation of the antenna.

It is also clear that the method is not linear in the range of salt concentrations that have been studied. The resolution is smaller at higher concentrations. This

contributes to the conclusion that the method must be used as a detector of anomalous salt concentration in the concrete and not as a means to determine the absolute values of concentration.

Relative measurements only need calibration against a large piece of metal. Then all values can be presented in dB relative this value.

Experimental Arrangement

In order to use the original SIR-system as a reflectometer the intensity of a particular part of the signal must be determined. This is impossible with the graphic recorder since it is a threshold recorder that does not allow the reading of amplitude differences in any other way than as a change of grey-scale in the radargram.

The previously described signal output is fed into a partial trace integrator, which has the ability to select an arbitrary part of the received signal and integrate that part. This yields an analog value which is digitized on a HP 3437 System Voltmeter and fed to a HP 85-microcomputer for storage and further processing.

Another way would be to record the entire waveform and then process it. The advantage with the chosen system is that the amount of data can be reduced by orders of magnitude by allowing a faster recording. The partial trace integrator allows 7 values/s of reflection intensity to be registered, which makes it possible to use a normal vehicle at a crawl and still get about 10 samples/m.

The partial trace integrator has two controls, one which sets the time when the integration starts, t_0 and one which sets the integration period, t , Figure 4.14.

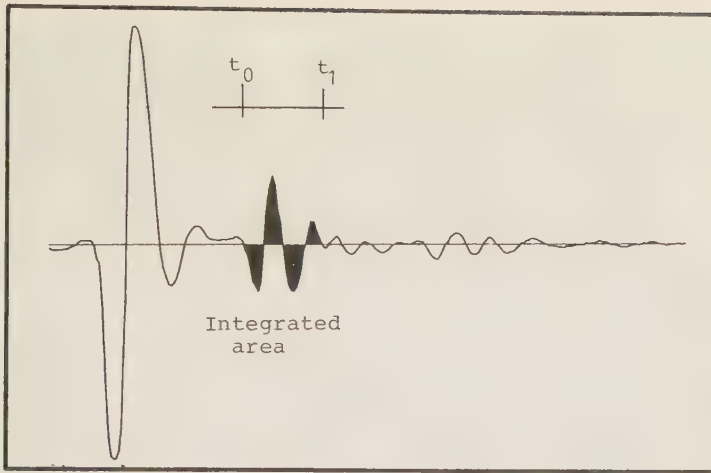


Figure 4.14. Integration parameters t_0 and t for the Partial Trace Integrator.

The shaded surface between the trace and the zero-line is integrated according to

$$I = \int_{t_0}^{t_1} |A(t)| dt \quad (4.6)$$

The antenna is mounted outside the vehicle according to Figure 4.15 when measuring alongside the vehicle and according to Figure 4.16 when measuring in front of the vehicle.



Figure 4.15. Experimental arrangement on the vehicle when measuring beside it. A=antenna F=flashlight

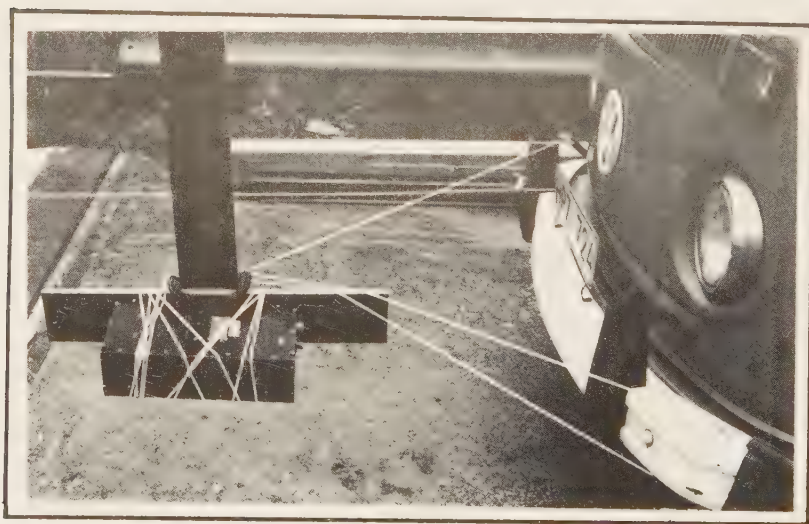


Figure 4.16. Experimental arrangement on the vehicle when measuring in front of it.

With the antenna mounted front left the survey can be performed along parallel lines with the vehicle in the right lane all the time.

The computer was programmed to set the value of the integral to zero when an interrupt-key was pressed on the keyboard. This was done each time the antenna passed 10 m fixes on the bridge and in that way the position of each sample was possible to calculate. In a future system the position will be determined from the number of revolutions of the speedometer-cable.

Field Test

Two bridges were selected on the grounds that there was a reasonable chance of damages and that the asphalt layer would be removed in the near future. The first was the bridge in Leksand, Figure 4.17. The surveyed area was the sidewalk on both sides of the bridge. The antenna was mounted at the right side of the vehicle. At 10 m intervals along the bridge paint-marks were previously put. In order not to disturb the circulation the survey had to be performed during the night. A flashlight mounted vertically front right projected a lit spot to the white line between road and sidewalk, ANDERSSON 1982. Keeping it there and observing the paint-marks the antenna position could be maintained above the center of the sidewalk, at an elevation of 0.6 m.

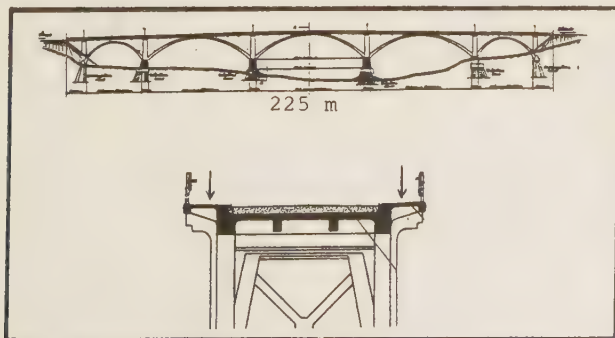


Figure 4.17. Leksandsbron, location of radar measurements.

The second object was Tunstabron between Rättvik and Borlänge. This bridge was surveyed in another way where the road area was covered with profiles at 0.5 m distance, Figure 4.18.

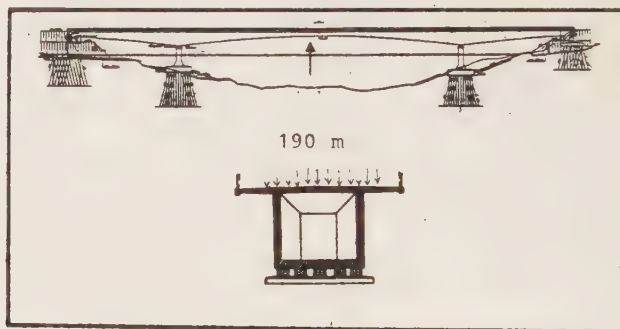


Figure 4.18. Tunstabron, location of radar measurements.

Also at one location, at the arrow in the elevation, a more detailed survey was carried out. This was done with the equipment shown in Figure 4.19. It makes it possible to move the antenna close to the surface and with a very low velocity for a distance of about 3.5 m. This was done along a joint in the concrete, 10 m from the zero momentum joint in the center of the bridge. The reason for choosing this location is that white salt shades are visible beneath the pavement according to the arrow in the elevation.

Subsequently the asphalt layer was removed from Leksandsbron, but this has not yet (September 1982) been done at Tunstabron.

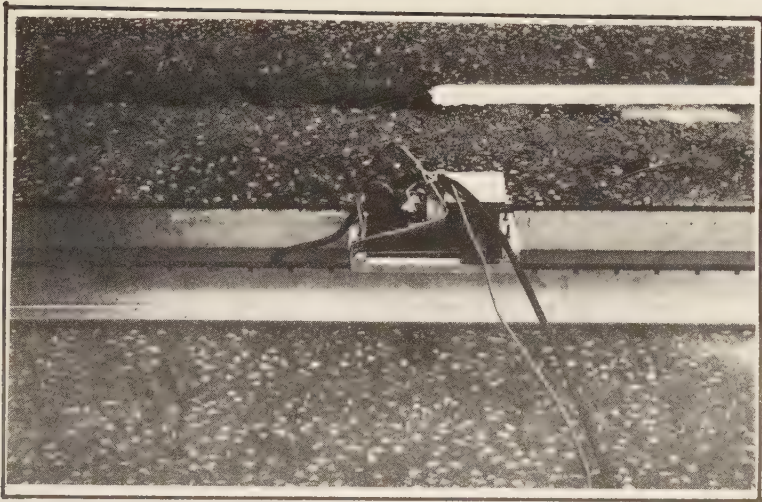


Figure 4.19. Motor driven wagon on rails used to move the 900 MHz antenna at a constant, low velocity for 3.5 m.

Leksandsbron

The data was collected in data bases containing 2000 samples. Since the bridge is curved in the vertical plane the vehicle moved at different velocities along the bridge. Because of this the entire side-walk is represented by 1800 - 2000 samples, which explains the varying horizontal scale of the profiles. The vertical scale is arbitrarily set to match the integral values. Since all measurements are considered relative there is no point in presenting any quantity at the vertical axis. It is sufficient to know that it is proportional to the integral value of the chosen period, t .

The raw data from Leksandsbron, for the northbound sidewalk is presented in Figure 4.20a and for the southbound sidewalk in Figure 4.20b. Profile 1 represents reflections after the first 5 half-periods while profile 2 represents the first 5 half-periods and profile 3 the two first half-periods. In Figure 4.21a and b the same profiles are presented after

processing with a running average of 9 samples. Below the profiles is the result from the subsequent evaluation of the damages when the asphalt layer had been removed.

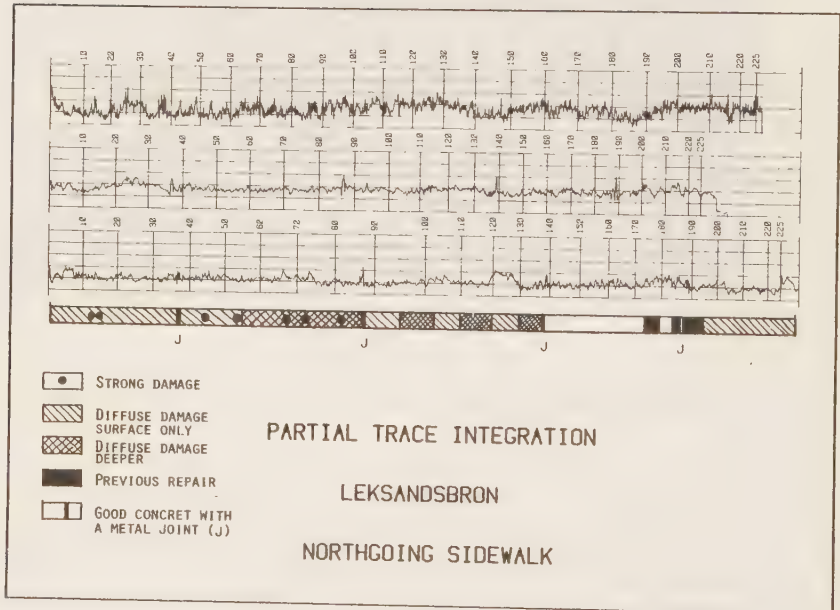


Figure 4.20a. Raw data from partial trace integration. Result from inspection of the concrete surface as the asphalt had been removed.

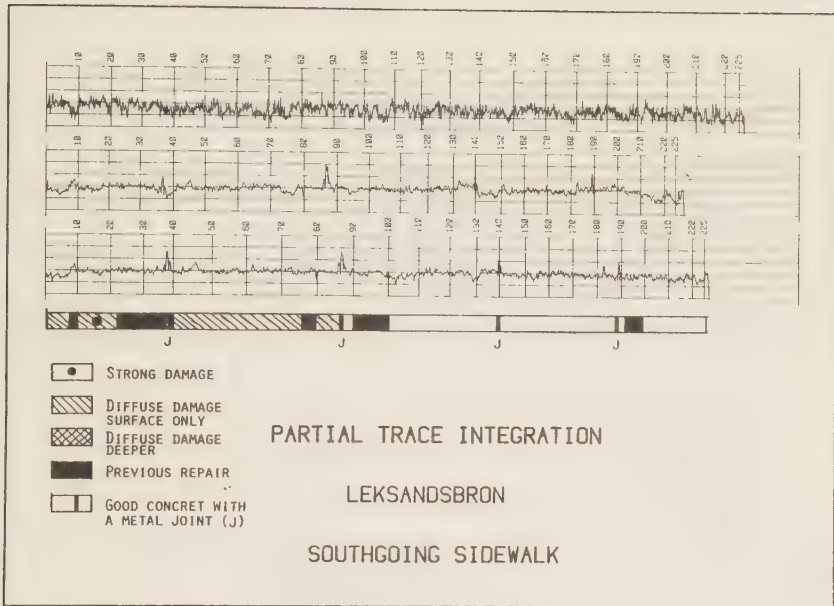


Figure 4.20b. Raw data from partial trace integration. Result from inspection of the concrete surface as the asphalt had been removed.

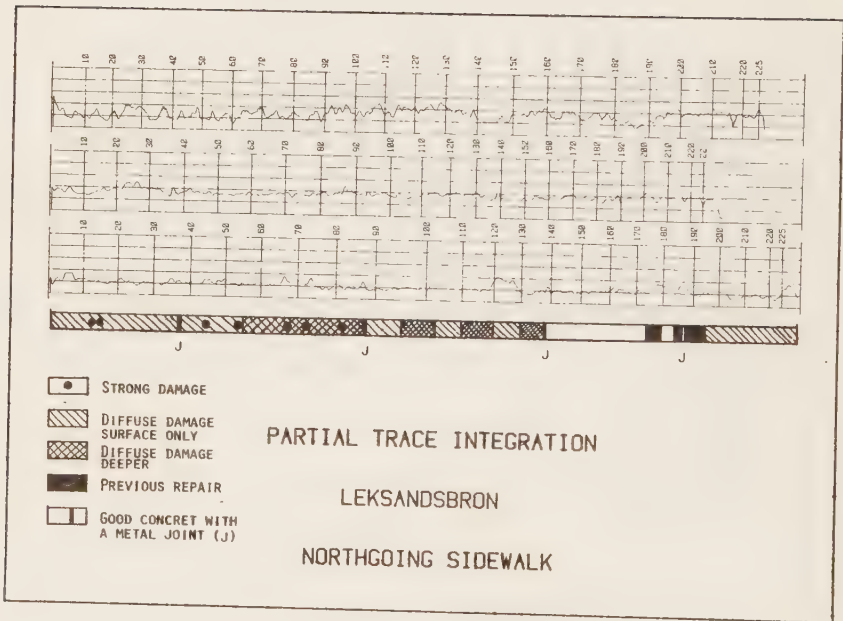


Figure 4.21a. Processing of the data in Figure 4.20a with a 9-sample running average. Result from inspection of the concrete surface as the asphalt had been removed.

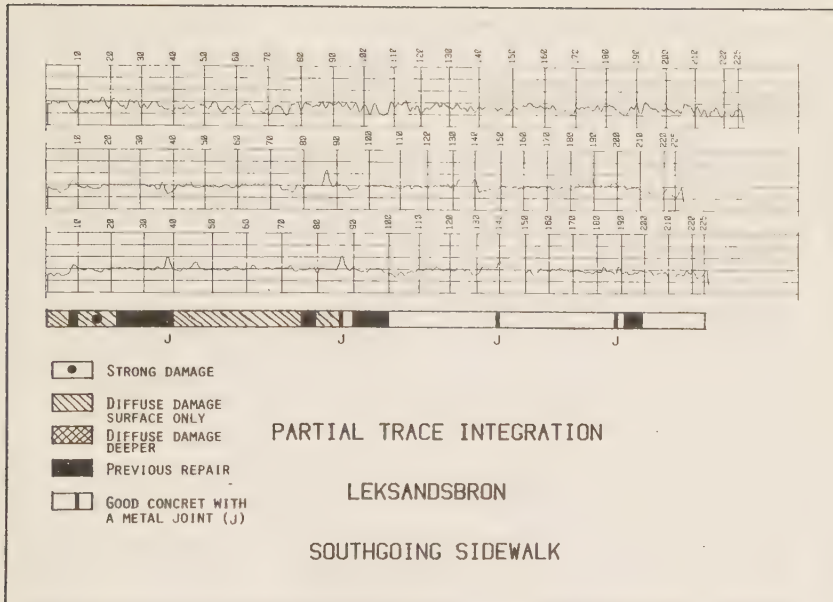


Figure 4.21b. Processing of the data in Figure 4.20b with a 9-sample running average. Result from inspection of the concrete surface when the asphalt had been removed.

In the chosen horizontal scale the running average simplifies the interpretation considerably.

This kind of experiment is difficult in that you may never know to what extent there is a damage until the asphalt is removed. This object turned out to have only a few serious damages i.e. a significant hole in the concrete where the structure had severely altered. Seven out of 8 holes are associated with peaks in the profiles but there are other

peaks of equivalent or stronger amplitude. For the northbound sidewalk the peaks in profile 3 around 70 m are outstanding. The strong wide peak between 120 to 130 m in profile 3 vanishes in profile 1 och 2 and is therefore attributed to a surface change of electrical parameters. It is evident that profile 3 gives the best indication of strong damages.

The inspection is complicated in that the salt concentration in the concrete may be high without the development of a severe damage. Thus not all areas producing peaks may appear as damages though they may have a strong salt concentration and be potential risks.

Tunstabron

The profiles are presented in Figure 4.22a and b. Since no removal of the asphalt has yet been done they may just serve as examples of a survey covering an entire bridge. It is interesting to note that at the center of the road there is a significant increase in the integral values in the areas of the supporting two pillars at 40 and 150 m. Of course these areas have the largest field moments and therefore have the strongest concentration of rebars. But it is also where cracks are most likely to occur in a bridge of this type, see Figure 4.18.

The detailed survey at 85 m in the northbound road and at 105 m in the southbound road is presented in Figure 4.23a and b. The pattern in these profiles is clearly sinusoidal, reflecting the passage of rebars. The salt shades beneath the pavement of the bridge are located just north of the joint. There is a distinct anomaly in the profiles 0.25 to 1.75 m in the northbound road and similarly in profiles 1.25 and 1.75 m in the southbound road.

The detailed evaluation of this test will be performed in about 1 year, when the asphalt layer will be removed.

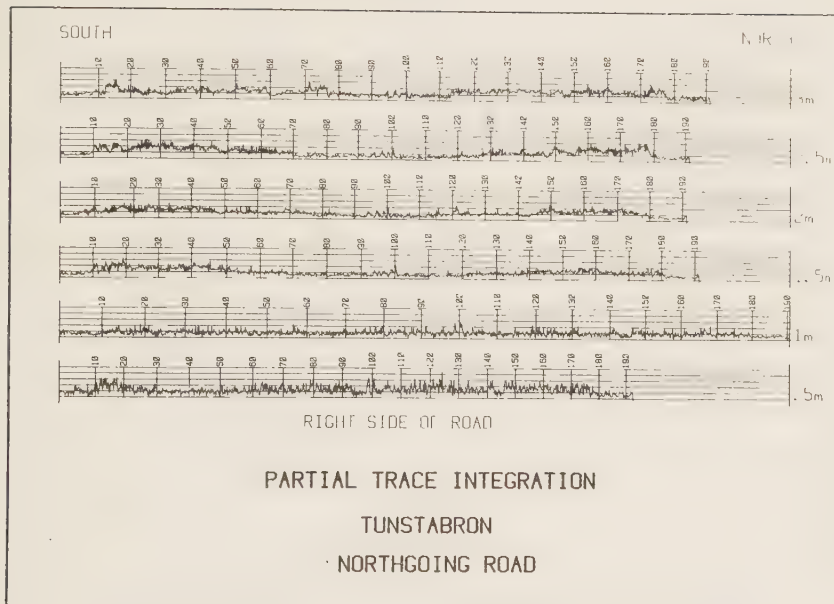


Figure 4.22a. Raw data from partial trace integration.

Conclusion

Experiments and field tests have confirmed the theoretical possibility that salt damages can be detected using the reflectivity as a parameter. The method is very rapid and undestructive and gives real time data. In minutes maps can be produced over the object of study. The method can probably only give relative results due to great variation of electrical parameters. Best results are expected in summer and autumn, when the salt is washed away from the pores in the asphalt.

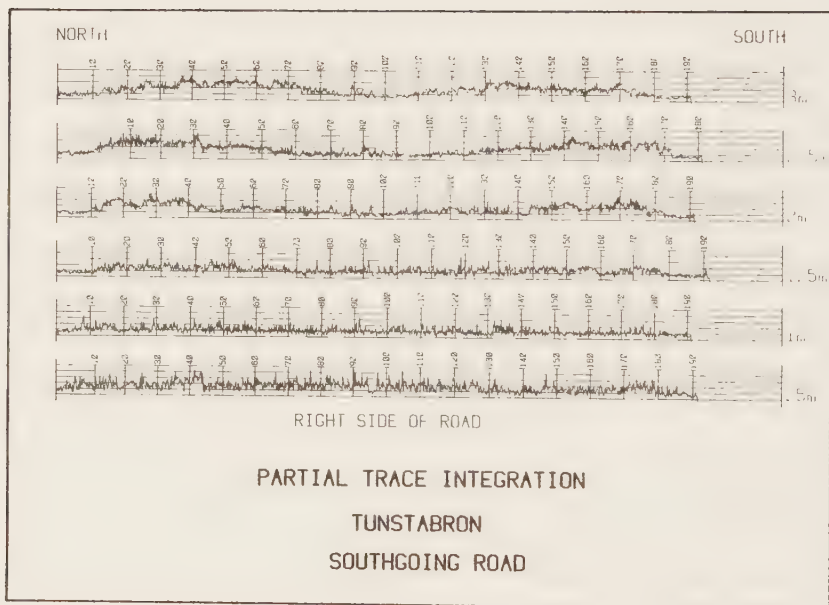


Figure 4.22b. Raw data from partial trace integration.

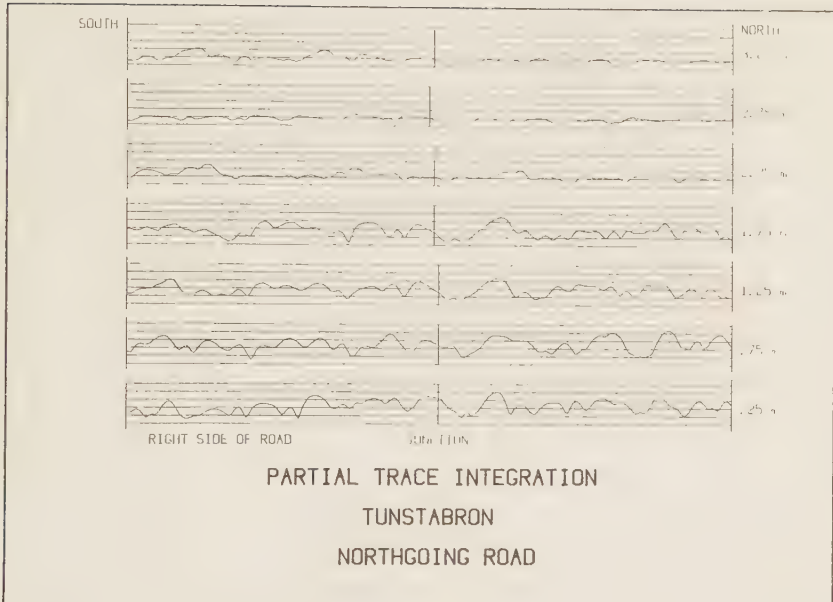


Figure 4.23a. Raw data from partial trace integration.
Profile length is 3.5 m around junction in position 85 m.

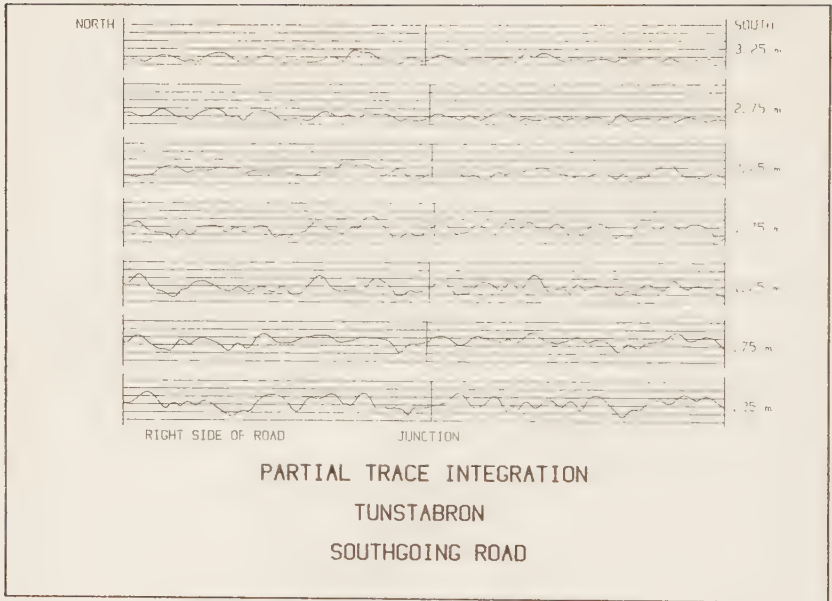


Figure 4.23b. Raw data from partial trace integration.
Profile length is 3.5 m around junction in position 105 m.

5 MEASUREMENT OF SOIL MOISTURE

Previous work

There are many examples of research in the remote determination of soil moisture with the use of microwaves and lower frequencies. The microwave measurements can be performed either in an active manner with the use of radar or in a passive manner using natural emission of microwaves and a multispectral scanner (MSS). Since high frequencies are applied small antennas are used and are therefore particularly suitable when the platform is a satellite or an aircraft.

Microwave reflectivity is a good indicator of soil moisture content but it only gives information about the uppermost centimeters of the soil.

Frequencies in the UHF-band require very large antennas to obtain directivity and are not suitable for remote sensing from airplanes or satellites. On the other hand these frequencies penetrate to a greater depth. UHF-measurements must thus be performed from the ground or from low-flying aircraft such as helicopters.

The property that can be measured is the magnitude of the return power relative to the transmitted power or to any other reference.

The bulk of results in this area uses the complex form of the relative permittivity. This convention leads to a new formula for calculating the reflection coefficient, r , when the radiation strikes the soil surface from nadir.

$$r = \frac{1 - \sqrt{\epsilon_r}}{1 + \sqrt{\epsilon_r}} \quad (5.1)$$

where the influence of the conductivity lies in the imaginary part of ϵ_r . The power reflection coefficient is calculated according to

$$R = \left[\frac{1 - \sqrt{\epsilon_r}}{1 + \sqrt{\epsilon_r}} \right]^2 \quad (5.2)$$

The complex form of the relative permittivity for water is described in KING and SMITH 1981, the so called Debye formula.

$$\epsilon_r = \epsilon' - j\epsilon'' = \epsilon_{r\infty} + \frac{\epsilon_{rs} - \epsilon_{r\infty}}{1 + j\omega\tau} \quad (5.3)$$

where

ϵ_{rs} = permittivity at $\omega = 0$

$\epsilon_{r\infty}$ = permittivity at $\omega = \infty$

τ = relaxation time

$\epsilon_{r\infty} = 5.5$ for microwave frequencies and ϵ_{rs} and τ are temperature dependant according to Table 5.1.

Table 5.1. Static permittivity, relaxation time, and critical wavelength of water ($\epsilon_{r\infty} = 5.5$). (From KING and SMITH 1981.)

T(°C)	ϵ_{rs}	τ (sec)	λ_c (cm)
0	88.2(89)	$17.8 \cdot 10^{-12}$	3.34
5	86.2	15.1	2.85
10	84.2	12.7	2.39
15	82.3	10.9	2.05
20	80.4	9.50	1.80
25	78.2(78.3)	8.31	1.57
30	76.7	7.36	1.39

The permittivity according to the Debye formula is complex and the real, ϵ'_r , and the imaginary, ϵ''_r , are calculated according to

$$\epsilon'_r = \epsilon_{r\infty} + \frac{\epsilon_{rs} - \epsilon_{r\infty}}{1 + \omega^2\tau^2} \quad (5.4)$$

$$\epsilon''_r = \omega\tau \frac{\epsilon_{rs} - \epsilon_{r\infty}}{1 + \omega^2\tau^2} \quad (5.5)$$

The variations of ϵ'_r and ϵ''_r with frequency is presented in Figure 5.1, from HOEKSTRA and DELANEY 1974.

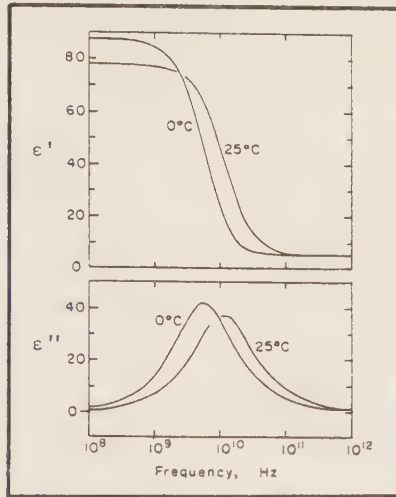


Figure 5.1. The dielectric relaxation spectrum of water at 0° and 25°C. [HOEKSTRA and DELANEY 1974.]

For frequencies below a few GHz the permittivity of water is almost constant according to theory, $\epsilon_{\text{eff}} = \epsilon'$ and $\sigma_{\text{eff}} = \sigma_0 + \omega\epsilon''$.

RUAULT and TABBAGH 1980, studied the permittivity of soils in the frequency range of 100 MHz to 1 GHz, and were able to show that this is also valid for soils, Figure 5.2.

They used discrete frequencies and found that at 216 MHz the humidity of the soil beneath the agricultural layer could be detected. This corresponds to a penetration depth of more than 30 centimetres.

They also discovered that for multilayered soil several frequencies should be used due to possible interference.

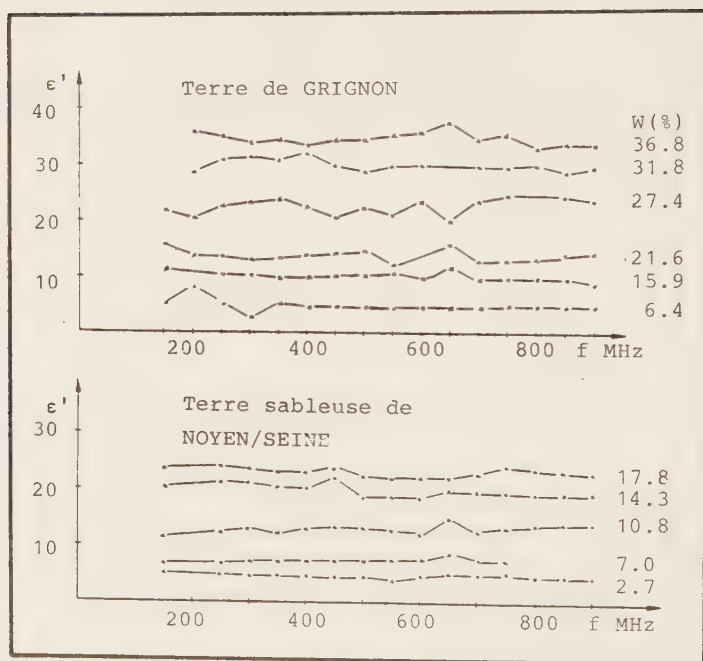


Figure 5.2. Variation of the real part of the permittivity with frequency and gravimetric water content, w . [RUAULT and TABBAGH 1980.]

From Figure 5.2 it is also possible to conclude that there is a strong relation between ϵ'_r and the water content, w , which the authors explained by an exponential relation of the form

$$\epsilon'_r = a \cdot e^{b \cdot w} \quad (5.6)$$

in contrast to the parabolic relation suggested by DAVIS *et al* 1977. These two types may give the same result for large parts of the range of interest.

Several scientists have studied the relation between relative permittivity ϵ_r and the moisture in soils. The moisture can be described in several ways, e.g. percentage by weight or volume or by weight water per volume unit.

NEWTON 1977 presents the data in Figure 5.3.

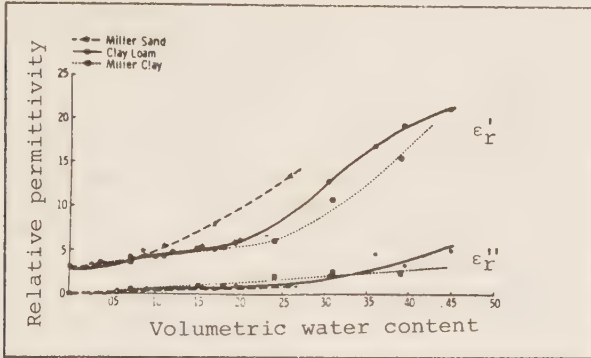


Figure 5.3. Relative permittivity of sand, clay loam and clay as a function of volumetric soil moisture at 1.4 GHz. [NEWTON 1977.]

The common explanation of these curves is that at low moisture values the water is tightly bond to the soil grains and thus has a lower permittivity than free water. At higher water contents water begins to act as the continuous phase and added amounts of water no longer increase the permittivity. This could also be explained by the fact that the tension in the pore water is very high at low moisture values and decreases when the moisture values increase. At very high moisture levels there is no longer any change in water tension. This phenomenon also explains why clay shows a lower relative permittivity than sand for equal moisture levels. Soil tension is dependant on the thickness of the water film surrounding each grain. The first molecular layers are more strongly tied to the grains than the subsequent layers. A soil with a large specific area will be able to bind an equal amount of water more strongly than

will a soil of small specific area. NEWTON 1977 presents a transformation of the data in Figure 5.4.

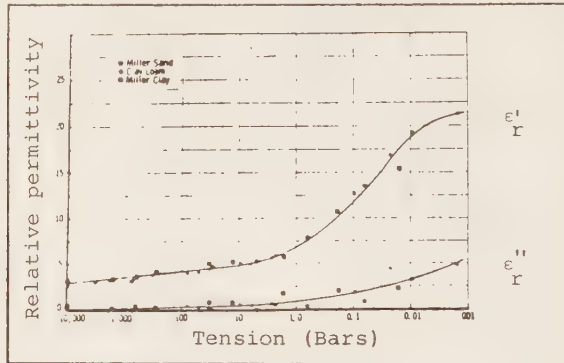


Figure 5.4. Relative permittivity of sand, clay loam and clay as a function of estimated soil tension at 1.4 GHz. [NEWTON 1977.]

In Figure 5.4, the difference between soils is eliminated and it seems that the relative permittivity is a general measure of the water tension in soils.

By using the data of Newton, DOBSON and ULABY 1981 found a linear relation between the power reflection coefficient in dB and the logarithm of the soil tension. The linear correlation coefficient is 0.99 and the relationship is given by

$$R(\text{dB}) = -1.232 \cdot \log(T) - 6.63 \quad (5.7)$$

This relation is presented in Figure 5.5 in combination with the data of NEWTON 1977.

DAVIS 1975 presents measurements of relative permittivity as a function of both depth and season for a sandy soil area. In this study a transmission line buried vertically in the soil and a time domain reflectometer were used. This gives an illustration of what might be expected from radar measurements, Figure 5.6.

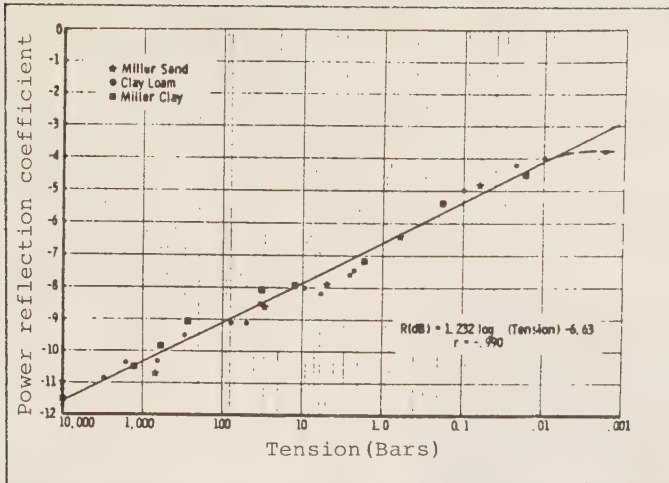


Figure 5.5. Power reflection coefficient R (dB) of sand, clay loam and clay at 1.4 GHz and at 0° (nadir) incidence. [DOBSON and ULABY 1981.]

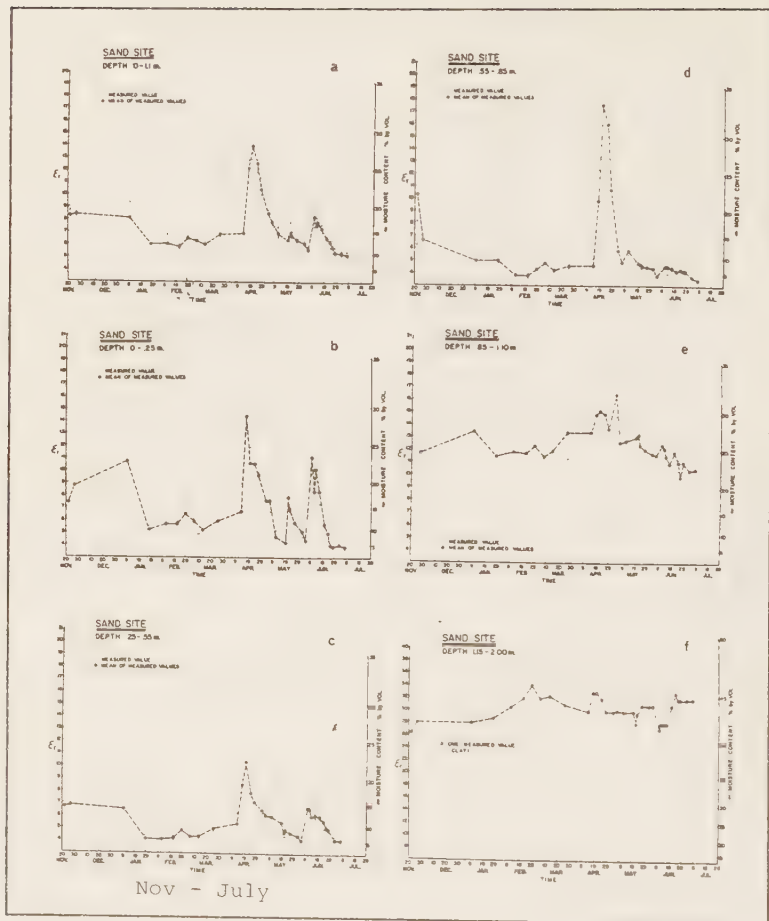


Figure 5.6. Relative permittivity of a sandy soil as a function of depth and season. [DAVIS 1975.]

Determination of Threedimensional Moisture Distribution (Pat. Pend.)

A true impulse contains all frequencies as is seen from Figure 5.7 which presents $f(t)$ (the real time data) and $F(\omega)$ (the frequency domain data).

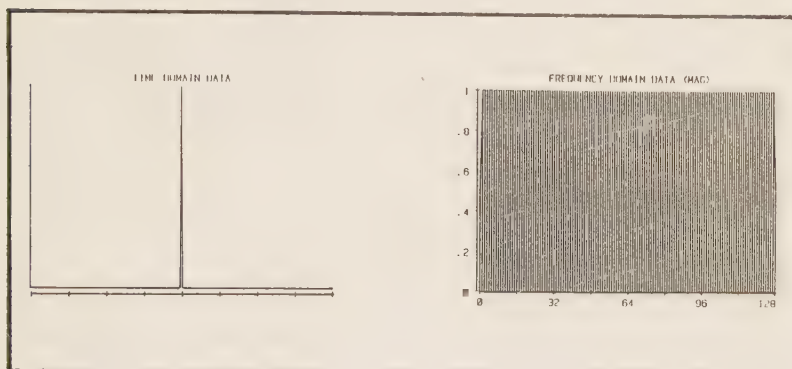


Figure 5.7. Real time data and its Fourier transform for a true impulse.

This impulse is not physically possible. Instead the typically transmitted waveform may be represented by the output of a 900 MHz antenna reflected against a large metal sheet, Figure 5.8.

The antenna is characterized by the center frequency and the bandwidth which is approximatively twice the center frequency. Antennas are available at center frequencies of 80, 120, 300, 400, 500, 900 and 1000 MHz, giving a total bandwidth of almost 2 GHz.

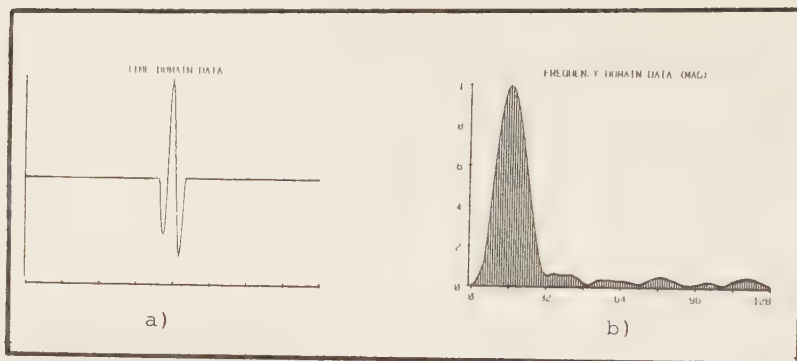


Figure 5.8. Real time data (a) and its Fourier transform (b) for a 900 MHz antenna impulse reflected against a large metal sheet.

When such an impulse strikes the surface of the ground the reflected power will vary according to the frequency. The skin depth varies inversely with the frequency, thus low frequencies penetrate to greater depths than high frequencies.

It may then be argued that the power reflection coefficients of high frequencies are dependant on the surface properties only while for low frequencies it depends on the properties of a thicker zone.

One may also assume that the low frequency component will experience a larger delay than will the high frequency components which only engage the surface layer.

What we can study is the shape of the returned impulse relative to an impulse from a known reflector e.g. a large

metal sheet. Consequently it is not adequate to use the skin depth as a measure of the volume engaged in reflecting different frequency components. This property describes the attenuation of the transmitted impulse only.

However the phase of the frequency component should reflect the delay time for each frequency involved. Since no reference oscillator exists the phase reference is taken as the phase values measured when the impulse is reflected against a known reflector, e.g. a large metal sheet lying on the ground.

When reflected against the metal all power reflection coefficients are 1 and the phase delays are those associated with the respective phase values of different frequency components in the transmitted pulse.

The phase delay, $t_{ph}(\omega)$, i.e. the delay of different frequencies is described by

$$t_{ph}(\omega) = \frac{\theta(\omega)}{\omega} \quad (5.8)$$

where

$\theta(\omega)$ = the phase of the angular frequency ω

The power reflection coefficient gives the average value of ϵ_r in the engaged volume for a certain frequency so that the associated velocity can be calculated. The phase delays subtracted by those obtained with reflection against a metal reflector makes it possible to calculate the penetration. This is because there is no penetration into the metal surface.

Assume that for a certain frequency the power reflection coefficient is R. Taking ϵ_r as the effective relative permittivity the velocity c is

$$c = \frac{c_0}{\sqrt{\epsilon_r}} \quad (5.9)$$

$$\sqrt{\epsilon_r} = \frac{1 + \sqrt{R}}{1 - \sqrt{R}} \quad (5.10)$$

$$c = c_0 \left(\frac{1 - \sqrt{R}}{1 + \sqrt{R}} \right) \quad (5.11)$$

where

$$c_0 = 3.0 \cdot 10^8 \text{ m/s}$$

The associated depth z when the delay time is t_p will be

$$z = \frac{1}{2} \cdot c \cdot t_p \quad (5.12)$$

These equations may not have found their final form, but serve as an indicator for the proposed method.

A requirement for this method is that the medium is nondispersive, i.e. the conductivity has a low value compared to $\omega\epsilon$.

Laboratory Experiments

Experiments were performed to check if impulse radar systems are useful for determination of soil moisture. All the experiments were performed with an antenna which had a center-frequency of 900 MHz.

The antenna was placed at an elevation of about 0.6 m above a wooden box 0.4 x 0.8 m containing the soil. The radar returns were digitized on a Hewlett Packard 3437 System Voltmeter and stored for later processing in a Hewlett Packard 85 desktop computer. The resulting returns are presented in Figure 5.9.

Dry sand was mixed with water to obtain different water contents measured as weight water/weight dry sample. It was determined from three samples taken at the surface of the soil immediately after the recording of the radar return.

For simplicity reasons soil tension is not used. This is not critical since only one type of soil was used.

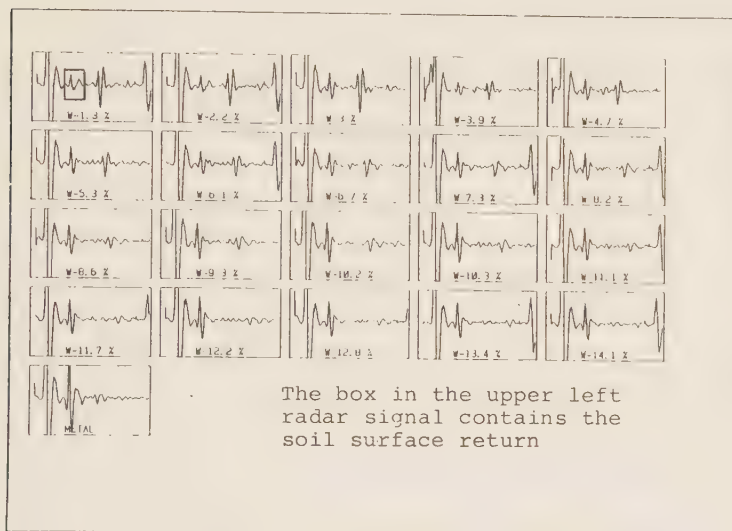


Figure 5.9. Radar returns for different water contents by weight (W) for a sandy soil and from a metallic surface (METAL).

The first return after the surface return in Figure 5.9 comes from the bottom of the box. As the water content increases it decreases. This does not necessarily depend on and increased attenuation in the soil but rather on the fact that more energy is reflected from the soil surface. The strong return at the right side of the signals is believed to come from any object in the vicinity of the box.

To get a reference the entire surface of the box was covered with a metal sheet producing a power reflection coefficient of 1. The maximum positive and negative amplitudes in this return was detected and the power reflection

coefficient calculated. All the data presented in Table 5.2 is given in dB relative to these values.

Table 5.2. Experimental data 900 MHz antenna transmitting against humid soil surface.

Water content (%)	A+ (dB)	A- (dB)	R (dB)
METAL	0	0	0
1.3	-7.6	-6.6	-13.3
2.2	-7.1	-6.2	-13.4
3.0	-4.6	-4.8	-10.1
3.9	-7.5	-8.2	-15.6
4.7	-5.4	-5.7	-11.8
5.3	-4.8	-4.5	- 9.9
6.1	-5.3	-5.4	-10.8
6.7	-5.1	-5.5	-10.7
7.3	-4.9	-4.8	-10.0
8.2	-4.2	-4.5	- 9.3
8.6	-4.0	-4.5	- 8.5
9.3	-3.0	-3.9	- 7.3
10.2	-2.4	-3.3	- 5.8
10.3	-2.8	-3.1	- 6.6
11.1	-3.9	-3.9	- 7.9
11.7	-3.7	-3.5	- 7.7
12.2	-2.6	-2.8	- 5.7
12.8	-3.5	-3.4	- 7.2
13.4	-3.5	-3.5	- 6.9
14.1	-3.2	-3.2	- 6.8

For clarity the data is also presented in Figures 5.10 - 12.

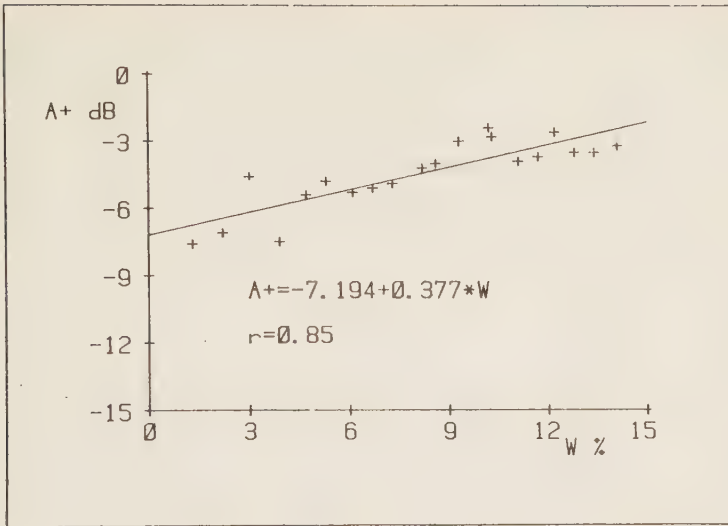


Figure 5.10. Maximum amplitude values in dB of radar return from the sand surface.

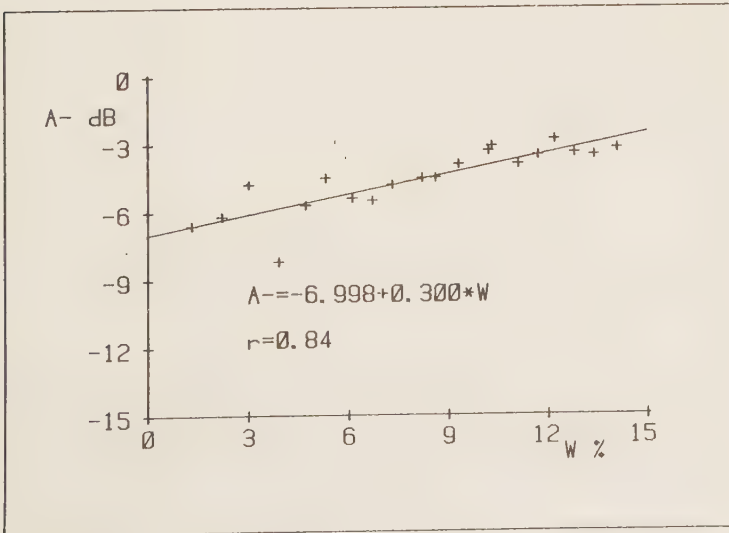


Figure 5.11. Minimum amplitude values in dB of radar return from the sand surface.

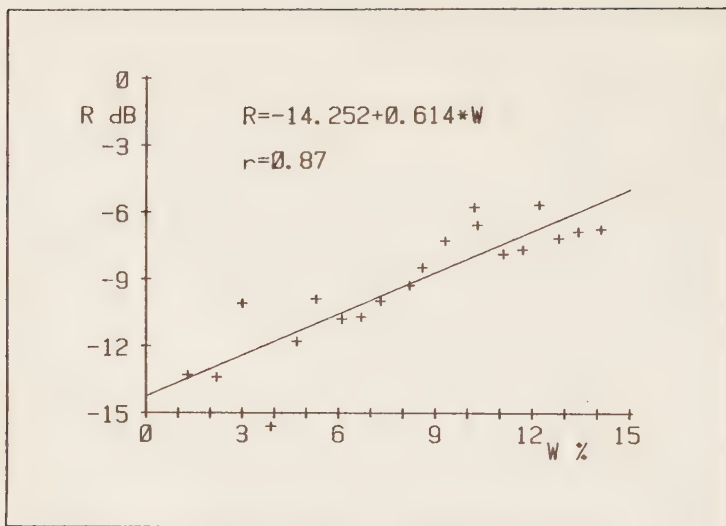


Figure 5.12. Power reflection coefficient in dB of radar return from the sand surface.

The three different parameters displayed in Figures 5.10-12 all clearly indicate that the radar return from the soil surface is strongly dependant on the water content. The best resolution is given by the power reflection coefficient. It also has the best correlation coefficient ($r=0.87$) compared to the amplitudes ($r=0.85$, $r=0.84$) respectively.

The main source of error is believed to be the nonuniform compaction that takes place in the surface of the soil when it is smoothed.

In the previous experiment the water content was assumed to be homogenous in the soil. The following experiment will show what happens when sand with initially homogenous water content experiences surface evaporation. The sand was placed in the same wooden box as before. A fan was mounted beside the box so that a continuous stream of air flowed over the

sand surface, thus increasing the evaporation. As before the antenna was mounted 0.6 m above the surface. Digital recording was made with the same equipment. Using an ordinary timer the equipment was turned on for 15 min periods at 12 h intervals. Finally one measurement was made ~ 5 days after the first series and the gravimetric water content profile determined in the box. The radar returns are presented in Figure 5.13.

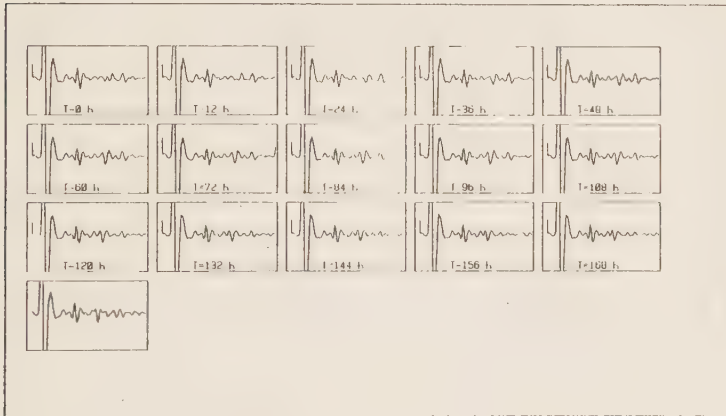


Figure 5.13. Radar returns from a sand surface under continuous evaporation.

This method of evaporating the water is rather efficient as long as there is a capillary transport of water to the surface. When the water content becomes too low the evaporation rate decreases. Physically it is the well known fact that after a short period of evaporation the surface is dry while a few centimeters below the water surface there is a sharp increase in water content. In this experiment there is no possibility to monitor the change in water content until the experiment is completed. The purpose is only to check if the predicted phase delay occurs.

It is important to note that the phase is only regarded as a relative value in this discussion. Since no reference oscillator exists, the reference has to be created. Phase is regarded as the relation in time between different frequencies in the transmitted impulse. The leading edge of the impulse is taken as a time reference. The corresponding delay time is named the signal front delay.

This gives a zero-time for the subsequent Fourier analysis of the radar return. As a reference for the phase delays, $t_{ph}^*(\omega)$, is taken the phase delays $t_{ph}^m(\omega)$ in an impulse reflected against a perfect reflector, a metallic sheet. So mathematically

$$t_{ph}^*(\omega) = t_{ph}(\omega) - t_{ph}^m(\omega) \quad (5.13)$$

where

$t_{ph}^*(\omega)$ = the requested phase delays

$t_{ph}(\omega)$ = the actually measured phase delays

$t_{ph}^m(\omega)$ = phase delays in an impulse reflected against a perfect reflector.

The skin depth in iron with $\sigma = 10^6$ mho/m is $1.68 \cdot 10^{-5}$ m and the phase delays in an impulse reflected against a metal sheet is therefore considered to reflect the phase delays in the transmitted signal.

Using the principles outlined here the phase delays of Figure 5.14 can be calculated, using (5.8). Plotted frequency band corresponds roughly to the 1/4 power level (-6dB).

From the data it is evident that the phase delays increase with decreasing water content and that the low frequency components are delayed more than the high frequency. This effect is more pronounced with increasing time.

It remains to explain why the 12, 24 and 36 h curves have parts lying below 0 phase delay, why the 0 h curve has more delay than the 12 and 24 h curves and finally why there is a dip at 1400 MHz.

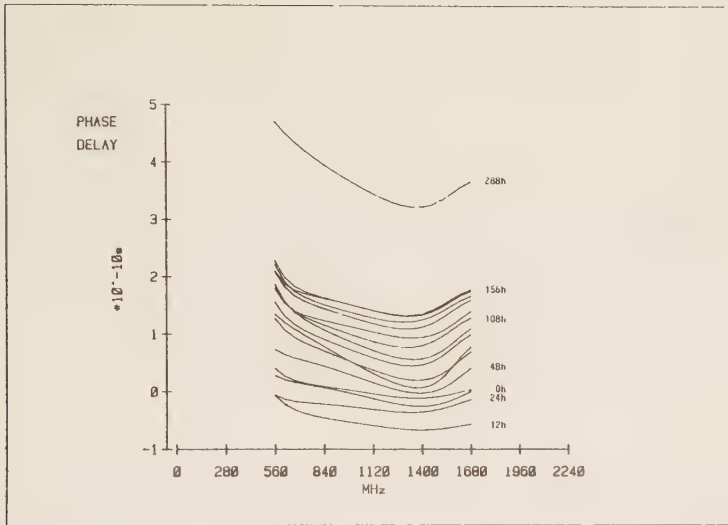


Figure 5.14. Phase delays in an impulse reflected against a humid sand surface under evaporation.

The vertical distribution of the gravimetric water content is presented in Figure 5.15, corresponding in time with the 288 h curve.

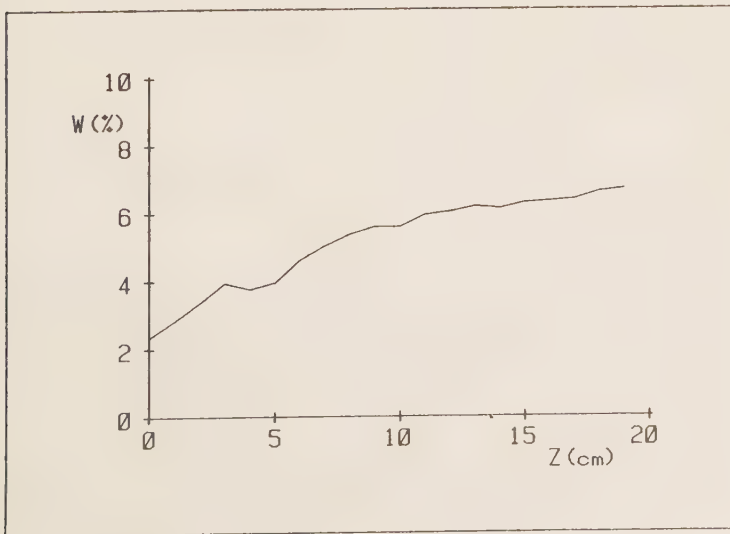


Figure 5.15. Vertical (z) distribution of the gravimetric water content ($t = 288$ h).

It is obvious that the water content has decreased from the initial 14.1 % in the entire volume, though more at the surface.

To compare with this distribution is the power reflection coefficient for discrete frequency bands $R(\omega)$ in dB at $t = 288$ h which is plotted in Figure 5.16. If the theory is correct the values should decrease with frequency.

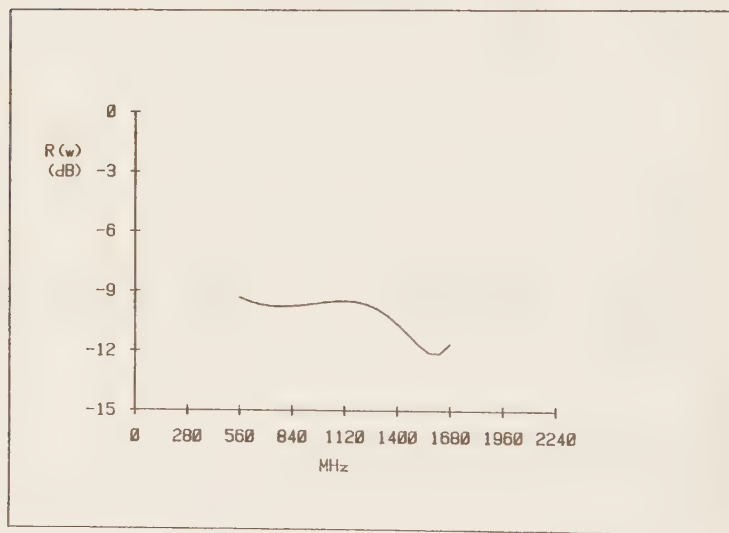


Figure 5.16. Power reflection coefficient as a function of frequency.

This is also roughly the case. High frequencies are associated with the dry surface layers and the lower frequencies with deeper, more humid layers. The values should be compared with those of Figure 5.12 which gives water contents in the range 3 - 8.5 %. These values are in reasonable agreement with the measured water content, especially if it is considered that they are average values for the engaged volume at every frequency.

Taking an example at 560 and 1400 MHz, $R(\omega) = -9.0$ dB and $R(\omega) = -11$ dB the phase delays are $t_{ph}(\omega) = 4.8 \cdot 10^{-10}$ s and $t_{ph}(\omega) = 3.1 \cdot 10^{-10}$ s. The corresponding $R(\omega)$ values are 0.126 and 0.079. Using (5.11) we get velocities $1.44 \cdot 10^8$ and $1.68 \cdot 10^8$ m/s. Using (5.12) the activated zone is calculated to have the depth 0.069 m and 0.026 m respectively.

Further experiments will be performed with antennas of lower center-frequency. 300 MHz is believed to be optimum for field use. The antenna will have to be mounted ~ 2 m above ground surface.

Finally the effect of interference was tested. The method was to fill a box with coarse gravel and let a water-table rise from the bottom of the box to the surface, Figure 5.17.

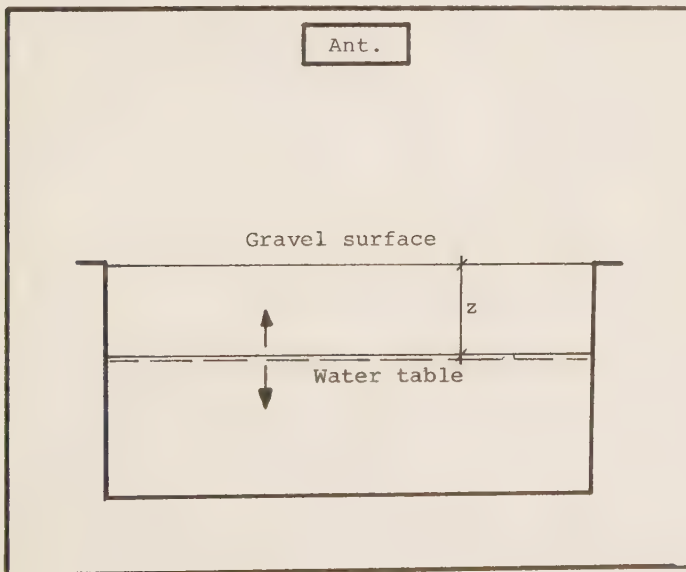


Figure 5.17. Experimental arrangement.

Interference of an impulse differs in two ways from continuous wave interference. Since the impulse has a finite duration no destructive interferences of higher order can take place. Since the energy is distributed over a

frequency band there will always be non-destructive interference frequencies that contribute to the return power. Consequently impulse interference can never reach a completely destructive level.

The return power $P(\omega, z)$ may be considered the sum of return power from the gravel surface $P_g(\omega)$, attenuated return power from the water-table $P_{aw}(\omega)$ and the interference factor $F(\omega, z)$, where the distance z is considered

$$P(\omega, z) = (P_g(\omega) + P_{aw}(\omega, z)) F_i(\omega, z) \quad (5.14)$$

where

$$F_i(\omega, z) = \cos^2 \left(\frac{\omega z \sqrt{\epsilon_r}}{c} \right) \quad (5.15)$$

The power reflection coefficients R_g (air/gravel) and R_w (gravel/water) are considered frequency independant. The relative permittivity for the dry gravel is ϵ_{rg} and for the saturated gravel ϵ_{rs} . The attenuation in the dry gravel is $\alpha_g(\omega)$. Then if the incident power is $P_o(\omega)$

$$P_g(\omega) = \left| \frac{1 - \sqrt{\epsilon_{rg}}}{1 + \sqrt{\epsilon_{rg}}} \right|^2 \cdot P_o(\omega) \quad (5.16)$$

and

$$P_{aw}(\omega) = \left[1 - \left[\frac{1 - \sqrt{\epsilon_{rg}}}{1 + \sqrt{\epsilon_{rg}}} \right]^2 \right] \cdot \left[\frac{1 - \sqrt{\epsilon_{rs}}}{1 + \sqrt{\epsilon_{rs}}} \right]^2 \cdot e^{-\alpha_g(\omega) \cdot 2z} \cdot P_o(\omega) \quad (5.17)$$

transmission reflection attenuation

The gravel used was a single fraction 8 - 12 mm which when dry has a relative permittivity $\epsilon_{rg} = 2.34$ and conductivity σ_g assumed 10^{-4} mho/m. When saturated $\epsilon_{rs} = 27$ and $\sigma_s = 1.6 \cdot 10^{-3}$ mho/m (HOFFMAN and OLAUSSON 1980.) With these values $R_g = 0.044$ and $R_w = 0.46$.

$P_o(\omega)$ is obtained from reflection against a metal sheet. With the data presented above, (5.14) takes the form

$$P(\omega, z) = [(1 - 0.044) \cdot 0.46 \cdot e^{-0.012 \cdot 2z} + 0.044] \cdot P_o(\omega) \cos^2 \left(1.53 \frac{\omega z}{c} \right) \quad (5.18)$$

or

$$P(\omega, z) = (0.44 \cdot e^{-0.024z} + 0.044) P_0(\omega) \cos^2(1.53 \frac{\omega z}{C}) \quad (5.19)$$

The result is plotted in Figure 5.18. The different curves reflect the effect of increasing the bandwidth from 100 MHz around the center frequency 900 MHz to the interval 0 - 1800 MHz, the total bandwidth of the impulse.

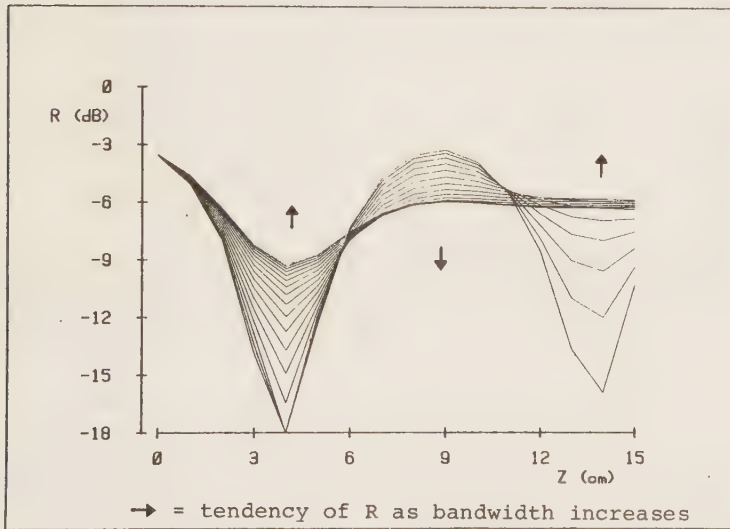


Figure 5.18. Theoretical interference of impulse for increasing bandwidth in a two layer media where the thickness of the upper layer is varied, according to equation 5.14.

From Figure 5.18 it is obvious that as the bandwidth increases the effect of destructive interference decreases. Also it seems that there will only be one dip in the interference pattern for the entire spectrum of the impulse. It is worth noting that the destructive z -values are constant as the frequency band increases, which is natural since the center frequency dominates the spectrum. Another interesting feature is that the amplitude of the second maximum decreases with increasing bandwidth.

The result of the measurements are presented in Figure 5.19, which displays only the part which is of interest in the radar return.

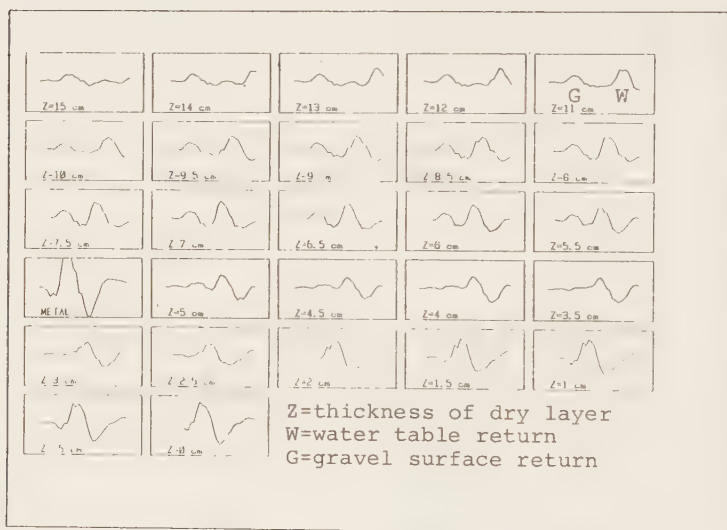


Figure 5.19. Radar returns from a box filled with gravel containing a rising water-table.

Figure 5.19 shows how the returns from gravel surface and water-table successively interfere. The first contact seems to occur around $z = 9$ cm. Maximum destructive interference takes place around 4 cm as predicted by theory.

In order to study the power return, the power of the samples containing the three first half periods of the waveform recorded for $z=0$ cm was calculated; the result is presented in Figure 5.20.

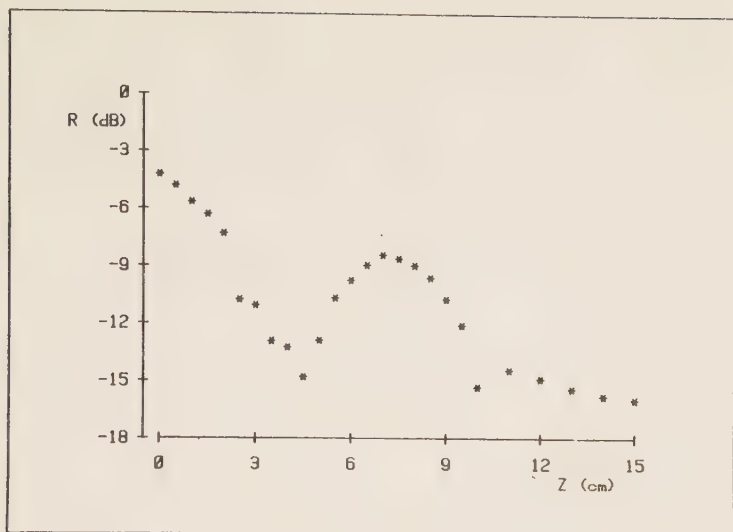


Figure 5.20. Return power in the samples containing the first three half periods of the return obtained for $z=0$ cm in Figure 5.19 for z -values 0-15 cm.

The values calculated for $z > 9$ cm are out of the interference range but are presented for completeness. They differ from the theoretical values in that there is no contribution from the water-table. Since this stands for $\sim 90\%$ of the power return (5.19) there is an expected 10 dB drop of energy as the water-table return moves out of the integration period. This is in excellent agreement with the measured data that gives $R = -15.92$ dB compared to the theoretical value $R = -6.42$ dB.

If the delay of the water-table return is considered a linear function of z , (5.19) can be modified to

$$P(\omega, z) = [(1-Q)(0.44 \cdot e^{-0.024z}) + 0.044] P_0(\omega) \cos^2(1.53 \frac{\omega z}{c})$$

where

$$Q = \frac{z}{z_m} \text{ for } 0 < z < z_m$$

$$Q = 1 \text{ for } z > z_m$$

z_m = the distance z when the watertable return has moved out of the integrated period of the radar return

This modified interference equation is plotted in Figure 5.21. The remaining difference between the theoretical model and measured data is attributed to the frequency dependant penetration of the impulse. It is probable that the spectrum has a displacement towards lower frequencies already at 4 cm layer thickness. This would explain the stronger dip in the measured data as compared to the theoretical curve of Figure 5.21. A value of $z_m = 10$ cm shows best fit to Figure 5.20

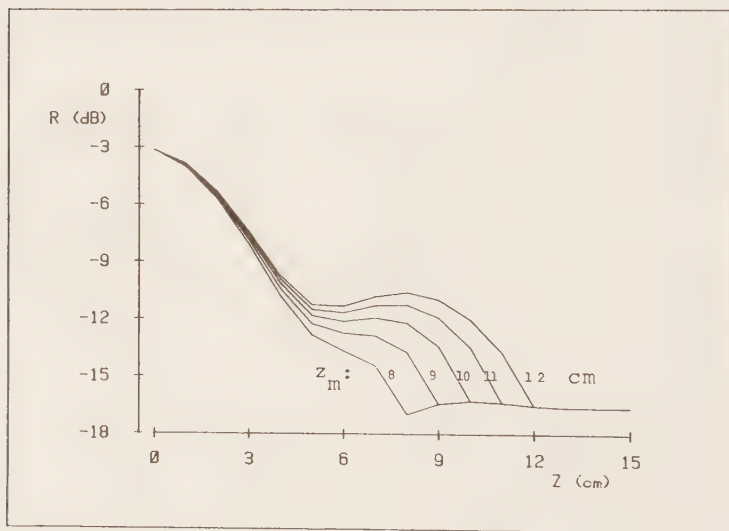


Figure 5.21. Theoretical impulse interference function for different distances z_m when the water table return has moved out of the integrated period of the radar return.

Conclusion

A conclusion of these experiments is that impulse radar shows good promise as a moisture detector and that it seems possible to determine the distribution of moisture also in the vertical direction. If the distribution is a step-function interference may occur. Due to the bandwidth of the

impulse, the destructive interference will not reach levels as high as when a single frequency measurement is performed. For a smoothly varying moisture content no interference will take place.

6 GENERAL CONCLUSION

This thesis is directed towards the experimental verification of some novel ideas concerning the use of impulse radar in civil engineering. Only to a limited extent are theories developed.

Impulse radar can record structures in the ground associated with changes in relative permittivity or electric conductivity. This is done by study of the delay times. The reflected waveform can be studied and give information on the electrical properties of the reflector. These properties may, in many cases, be attributed to specific phenomena and consequently work as indicators of these. This requires digital recording.

If the vertical average of the relative permittivity is constant the thickness of a layer may be determined. This is tested on a large scale for peat bogs with excellent results. Radar profiling gives continuous data on peat thickness which is valuable for scientists and the peat industry. Due to the continuous nature of the data most obstacles in the peat can be detected and planned for in the exploration process.

In other soils it may be difficult to obtain an accuracy as high as in peat due to the variance in the groundwater table. This only means that the vertical position of structures, as determined by radar delay times, may be a little uncertain. The horizontal position of e.g. a subsurface rock unconformity, is exactly determined as are the structures inside the soil.

The same as for soils is applicable to the sedimentary rocks while the crystalline rocks are expected to show constant values of relative permittivity, thus allowing precise range determination.

Studies in freshwater includes determination of water depth and bottom and subbottom structures. Since the relative permittivity of freshwater is constant, the determination of water depth is straight forward. The power reflection coefficient is believed to make it possible to separate different bottom soils.

An advantage with the impulse radar compared to sonar is that surveys can be performed from the ice surface. This makes it possible to get very accurate positions and survey shallow waters that are not navigable by boat.

Corrosion is an important problem concerning pipe burial. The most dangerous zones are where the resistivity changes drastically. Since the electromagnetic waves are attenuated in proportion to the inverse value of the resistivity, the shape of the radar return can be used as a parameter for detecting dangerous zones. Once these are detected the absolute value of the resistivity change can be determined with two conventional resistivity measurements.

The management of hydroelectric power plants requires advanced regulation of water dams. One input parameter is the equivalent water content in the snow cover. Provided that the measurements are performed late in the season, when the snow density is high, impulse radar has proved capable of determining the equivalent water content from delay times. The method requires a small number of reference samples to establish the linear relation between delay time and equivalent water content. It is also believed that the surface return has potential in determining whether there is free water in the surface of the snow cover.

Old concrete constructions are easily damaged if salt penetrates into them. This is especially serious in bridges that can suffer severe loss of strength. Since salt has a much higher electrical conductivity than concrete, the reflectivity of a concrete surface is stronger if the concrete contains salt. Thus by moving an impulse radar antenna over the construction salt damages can be located using the reflectivity as a parameter.

It is well known that the power reflection coefficient for microwaves is proportional to the water content of a soil. Due to their high frequency they are severely attenuated and

only give information on the uppermost centimetres of the soil. By using impulse radar in the UHF-band penetration increases and information on soil water content is obtained for a larger depth. Since the impulse contains frequencies ranging from zero to twice the center frequency of the antenna chosen, it is possible to study the power reflection coefficient for various frequencies and thus get information on the vertical distribution of water content in the soil. Then by moving the antenna above the area of survey, the threedimensional distribution of water in the soil can be determined.

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